Sequences of Niche Strategies: An Exploratory Multiple-Case Study in Automotive

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Sequences of Niche Strategies

An Exploratory Multiple-Case Study in Automotive

by

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EXECUTIVE SUMMARY

In the context of diffusion of innovation, strategic niches that emerge prior to mass-market adoption represent an important area of focus for radically new technologies, since these are typically introduced in several such subsequent niches. A niche strategy represents a response to circumvent a market situation characterized by hampered large-scale diffusion, by which a company deliberately focuses on strategic niches in the effort to either (1) develop a marketable product application or (2) market an already developed product in the existing regime, if and only if revenue can be derived from the market introduction. Ortt et al. (2013) reported ten generic niche strategies.

Departing from the presumption that niche strategies can influence the market situation on the basis of which they arise, the notion of a sequence of niche strategies was conceptualized. It is defined as a series of niche strategies, in which the subsequent instances of the sequence are linked between one another on the basis of a specific rationale; the rationale can be based on either an emergent or deliberate logic.

Using an exploratory multiple-case study research design, three automotive technologies were investigated: dual-clutch transmission, anti-lock brakes, and polymer exchange membrane fuel cell vehicle. The goal was to observe how sequences of niche strategies can be used for market creation. The following research questions were addressed:

1. What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?
2. How do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?
3. Why do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?
4. Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?
5. What could be the logic and rationale behind sequences of niche strategies for market creation?
6. What are logical sequences of niche strategies in the selected industry?

The findings show that overall there is no consistent pattern in the dynamic of the barriers to large-scale diffusion. Three drivers can influence the barriers: (1) niche strategies, (2) external factors and (3) the change from one market to another. Among the three, external factors have the largest scope. Furthermore, except for 'accidents or events', for all of the core and contextual factors which were (partly) removed by niche strategies, there is an available external factor to double that influence.

Another interesting observation on the topic of external factors is that they are of two kinds: purely external factors –such as an economic downturn, autonomous improvements in other industries– or factors external to the particular niche strategies, but connected nevertheless to the market actors –such as internal R&D, lobbying by OEMs, etc. The latter ones can be seen as alternative or additional ways in which actors can guarantee or improve the success of current, or respectively future, niche strategies.

'New high-tech product' and 'customers' were found to be more prevalent than the other barriers. Fortunately for managers, these barriers also feature the largest cumulative array of external factors and niche strategies which may influence them.

One of the contributions to science represents the finding that niche strategies need not necessarily circumvent or diminish the magnitude of barriers. They may also create new barriers, which had been eluded by the literature. This entails that managers should be well informed of the potentially unintended consequences on the market context, before deciding to introduce the product via a niche strategy.

Wait-and-see niche strategy proved effective when combined with internal product development, monitoring and change of the market context, and influence on the barriers via external factors. Niche strategies are an option when there are remaining barriers to large-scale diffusion. The strategy of large-scale introduction should be considered in the absence of barriers, but mass production facilities may be commanded even earlier than that; for e.g. when economies of scale are essential in decreasing the manufacturing costs. Lastly, mass market strategies can be conceived when there are remaining barriers, provided that the core factors can be removed via external factors.

Three generic types of sequences were observed: (1) exploitation- or (2) exploration-oriented emergent ones, and (3) exploitation-oriented deliberate ones. Under this typology several sequences were uncovered, each addressing a certain rationale: for (1) they were changing market context, competitive response, diminish magnitude of barrier(s), and technology visibility; for (2) search for customer segments, and revenue diversifying efforts; and lastly for (3) market skimming, and removal of barrier(s). The sequences for each logic and rationale were very much case specific, and dependant on the initial market context and on the dynamics of the barriers.

The development of the theory on the topic of sequences of niche strategies shows potential. The most important aspects left to be investigated by future researchers are: (1) performing an investigation of the impact of each individual niche strategy from the sequence on the factors, (2) detailing the concrete mechanisms by which niche strategies can impact the market context. Furthermore, greater managerial benefits would be derived if it could be identified how the combined effect of niche strategies and external factors could be leveraged as part of a sequence.

Finally, among the significant contributions to science, the following are recalled: a dynamic model for market contexts, niche strategies, external factors, and the relationships between one another; the definition of niche strategy and sequence of niche strategies; the methodology for the investigation of sequences; revisions to the model on the pattern of development and diffusion by Ortt and Schoormans (2004); and lastly revisions to the model of niche strategies by Ortt et al. (2013).

In this latter regard, several aspects have been suggested. Firstly, corrections should be made to the list of contextual factors: capital –or financial resources– was added to 'natural resources and labour', and 'installed base' was observed as new separate contextual factor. Secondly, the list of niche strategies was revised. The former 'redesign' niche strategy was split into 'technological redesign' and 'social redesign'. 'Leasing' niche strategy was uncovered as an entirely new addition to the list; entailing the lease of the good in order to circumvent the prohibitive price barrier.

Promising managerial implications ensue from the results. Among these, an important finding remains the cautionary word of advice towards the use of niche strategies. This decision can detrimentally influence the market context, since it may lead to the creation of new barriers – or current one(s) might be increased. Secondly, the impact of external factors was more consistent towards decreasing the magnitude of the barriers among the three change drivers, and they had shown the largest scope. Managers can leverage these factors –primarily those under the decision authority of the central actor– to alter the market context without the need for product introduction.

ACKNOWLEDGEMENTS

The culmination of this thesis is as much the impact of the sustained research work, as it is the influence of the supportive environment created by a selected number of individuals. I reserve the space herewith to express my gratitude to them.

Firstly, I would like to thank my supervisors for their guidance, and for constantly challenging me to shift my perspective. Perhaps most indicative of this aspect were our fruitful discussions, which would more often than not span outside the intended initial scope. But at the boundaries of what I had formerly not considered stood some of the most interesting implications for the research.

More specifically, I would like to express my gratitude to Dr. J.R. Ortt for having sparked my interest in innovation systems, and for supporting me to pursue the topic. His knack for visually synthesising seemingly disparate ideas, critical thinking and coaching were of great help. Equally so, I would like to thank Dr. L.M. Kamp for the motivation she has given me throughout the thesis work. Her keen eye for detail, the difficult –yet much needed– questions with regard to the research results, and her experience in another field were much needed.

Secondly, I would like to express my gratitude to my parents who had supported me throughout this journey. For my mom goes a special thank you for teaching me the value of always be willing to take an extra step. For my dad I want to thank him for balancing the former mindset with a constant reminder of the greater picture. This succinct list barely attests to all the aspects for which I am grateful to them.

Lastly, I would like to thank my girlfriend for her constant support. It would probably take me the next couple of years to return all the lost weekends she had spent by my side, with an undeterred motivation. I can only help to do the same for her upcoming thesis work.

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CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

1. INTRODUCTION

Diffusion of innovation, particularly of radically new technologies, has received significant attention from scientific literature (see Moore 1991; Rogers 2003). Typically, mainstream literature assumes the standard S-curve diffusion model (Ortt & Schoormans 2004).

But upon closer inspection, many radically new technologies are introduced in niche markets, and only later a mass market emerges (Levinthal 1998). Empirically, typically 80% of new high-tech products are first introduced in market niches prior to the emergence of a mass market (Ortt 2012). "Lynn et al. (1996) argue that firms might use niche markets as a strategy to 'test' the innovation in different market settings" (van der Laak et al. 2007, p.3216), and from a managerial perspective they can be seen as a transition path towards mass markets (DeBresson 1995).

Across the literature, niches are seen to elicit important characteristics "for the broader diffusion and development of the new technology" (Weber et al. 1999, p.16), such as: demonstrating the viability of a new technology[,] providing financial means for further development, […] build a constituency behind a new technology and set into motion interactive learning processes and institutional adaptations in management, organisation and the overall institutional contexts" (p.16).

The following three sections of this chapter describe the research problem, the objective and the research questions. In section 1.4, the scientific and managerial relevance of the current work are presented. Section 1.5 shortly presents the research approach, and lastly section 1.6 details upon the structure of the report in connection to the research questions.

1.1. RESEARCH PROBLEM

The introduction on the topic of niche markets is relevant to the context of the thesis work, since the literature on 'niche strategies' has been recently enriched by the insights of Ortt et al. (2013). Their results offer promising new avenues; as the authors note "[f]urther research is required to better understand how the 10 different niche strategies can be used to create new markets" (Ortt et al. 2013, p.10). They are referring to the fact that some of the niche strategies do not merely circumvent the barriers hampering large-scale diffusion; in fact, they are found to actually exert an influence on these barriers. For example, the 'top niche strategy' "is adopted in case the price of the product is too high for a mass market introduction" (p.10). On one hand it influences the group of 'contextual factors' by allowing the company to learn about the technology; and on the other hand it also affects the group of 'core factors', since it "slowly increases production rates, reduces the price and [thereby] creating a larger market" (p.10).

To sum up, there is a gap in the literature with regards to how the 10 generic niche strategies can be used to create new markets, in particular on how the choice of niche strategies influences the 'core' and 'contextual factors'.

Furthermore, in several industries, Trevino Barbosa (2011) reports that radically new high-tech products were introduced –on average– in three market niches prior to large-scale diffusion. This suggests that managers would benefit from knowing not only how the niche strategies can be used to create new markets, as proposed above by Ortt et al. (2013), but also from understanding how sequences of niche strategies can be used in the same respect. In spite of that, the literature on this topic is absent.

In conclusion, the main problem to be addressed by this research is the lack of available literature on sequences of niche strategies. By targeting this problem, the research should also address the limited information on how the 10 generic niche strategies –hypothesised by Ortt et al. (2013)– can be used to create new markets.

1.2. RESEARCH OBJECTIVE

The objective of this research is to explain how sequences of niche strategies can be used to create new markets by analysing a set of cases from the automotive industry.

By sequence of niche strategies, the current document refers to time-series of subsequence niche strategies, provided that there is also logic linking the niche strategies. In order words, the niche strategies must contribute towards an overarching goal of the sequence.

For example, let us take the hypothetical scenario of a radically new metal that has recently been discovered. In this case, the poor and early knowledge of the technology (i.e. contextual factor) may lead to a lack of readily available production systems (i.e. core technological and market factor). Thus, the product will be produced in small amounts, by manual labour, and sold to a limited group of customers who are willing to pay a premium. This represents a 'top' niche strategy that arose on the basis of the pair of factors 'knowledge of technology → production system'. After a couple of years, due to the accrued learning, the manufacturing rates slowly increased and mass production is achievable. However, because the manufacturing process depends on a scarce resource (i.e. contextual factor) the high-tech product cannot be produced at an affordable price (i.e. core technological and market factor). Since the metal has important social benefits, the government has committed to subsidize its commercialization. This represents a 'subsidized niche strategy', which arose on the basis of the pair of factors 'resources → new high-tech product'. Note that in this case this latter pair of factors is different from the former. After some more years, as a result of the learning accrued from the subsidized production an affordable replacement for the scarce resource is found. Also, there are no more core technological and market factors hampering large-scale diffusion. In this hypothetical scenario, the sequence of niche strategies was 'top niche strategy' – 'subsidized niche strategy'. The overarching goal of the sequence was the removal of the prohibitive price.

Hoogma (2000, p.19; based on Mintzberg & Waters 1985) uses the definition of strategy as a "pattern in a stream of decisions", and distinguishes between deliberate and emergent strategies. The former are patterns "realized as intended" (Hoogma 2000, p.19), while the latter are patterns "realized despite, or in absence of, intentions" (p.19). The current research aims to explore both deliberate and emerging sequences. For the hypothetical scenario presented above, had the influence of the niche strategies on the barriers been known upfront –i.e. before the first market introduction– the sequence would have been emergent. However, had the two niche strategies been a response to the changing market context that would simply allow for this optimal order, the sequence would have been emergent. In either case, the research deliverable would identify that the sequence 'top niche strategy' – 'subsidized niche strategy' was useful in that particular market context and that specific rationale.

1.3. RESEARCH QUESTIONS

The following section will detail upon the research questions. The section is structured as follows: firstly, an overview of the research questions will be presented; secondly, the connection between the research question and the research objective will be shortly detailed upon.

The research questions are as follows:

1. What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?
2. How do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?
3. Why do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?
4. Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?
5. What could be the logic and rationale behind sequences of niche strategies for market creation?
6. What are logical sequences of niche strategies in the selected industry?

The first research questions lays down the methodological approach for the investigation into sequences of niche strategies. The second and third research questions describe and explore the change in the market context. The fourth question attempts to identify the criteria for which companies opted between the three types of strategies. In order to answer the final research question, the inherent question would be: to what purpose would these logical sequences of niche strategies be used in the selected industry? Therefore, the need for asking research question no. 5 prior to it.

1.4. RELEVANCE

1.4.1. SCIENTIFIC RELEVANCE

Several gaps in the current body of literature were found with respect to niche strategies, as formulated by Ortt et al. (2013), and the topic of sequences of niche strategies. The results of the thesis work are expected to contribute towards the following knowledge additions:

1. Firstly, the up-front scientific relevance can be derived from the research objective. By investigating the concept of sequences of niche strategies the foundation will be laid for future avenues in this direction, including operational measures and methodological tools. The definition of 'niche strategy' is not explicitly depicted in the seminal paper to this research, and by addressing this gap the model would be improved; sequences of niche strategies need also be defined.
2. Secondly, an important aspect of dynamics is expected to be added to the current static model of niche strategies developed by Ortt et al. (2013). Furthermore, the model of niche strategies had not been tested towards the current goal, and would therefore constitute an additional application of the model on a repetitive basis during the market adaptation phase of radically new high-tech products.
3. Thirdly, the exploration of the logic and rationale behind sequences of niche strategies represents the earliest of works in the direction of a theory. The current research results can be indicative of the potential of such a theory.
4. Lastly, industry-specific sequences may be uncovered. Although the literature is not void of papers documenting sequences of niches (or niche applications) in one selected industry, sequences of niche strategies were not found to have been formerly attested.

1.4.1.MANAGERIAL RELEVANCE

From a managerial perspective, the thesis work provides useful information for companies. They will be able to leverage the dynamic conceptual model towards a better understanding of the changing market context. The specific influence of niche strategies on the barriers would help managers uncover or confirm ways to alter the core factors. Lastly, observed sequences may be used as templates for future product introductions.

1.5. RESEARCH APPROACH

The research approach is that of multiple-case studies. Study questions that are suitable for case study design are those of the form “how” and “why” (Yin 2003). The case study design is thus in line with this research, since the research objective attempts to explain *how* sequences of niche strategies can be used to create new markets. Chapter 4 is reserved exclusively towards this purpose.

1.6. REPORT OUTLINE

Table I depicts the connection between the research question and the different parts of the report. In addition, the reader is advised to note that chapters 2 and 3 lay down the theoretical foundation for the subsequent investigation; the reporting of the case studies from chapter 5 represents the factual evidence on the basis of which research questions no. 2 to 6 are answered.

Table I: Research questions and corresponding chapters

Research question	Chapters
1.What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?	4.
2.How do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	6.2.1, 7.1
3.Why do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	6.2.2, 7.2
4.Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?	6.3, 8
5.What could be the logic and rationale behind sequences of niche strategies for market creation?	6.4.1, 9.1
6.What are logical sequences of niche strategies in the selected industry?	6.4.2, 9.2

2. SCIENTIFIC BACKGROUND

2.1. TERMINOLOGY

2.1.1.RADICALLY NEW TECHNOLOGIES

Radically new technologies are defined as "radically new in the market and state-of-the-art in their respective disciplines" (Ortt 2012, p.1), whereby:

- "radically new in the market means that the functionality was new to the market or the price-performance ratio was much better than contemporary products" (Ortt 2012, p.1)
- and "state-of the art in their respective disciplines means that the products were based on new technical principles […] or were based on an existing principle but with a much better price/performance ratio" (Ortt 2012, pp.1–2)

2.1.2.NICHE MARKET

Many radically new technologies are introduced in niche markets, and only later, a mass market emerges (Levinthal 1998). "*Niche markets* can be special geographical locations, but also specific application domains, which act as stepping stones for wider diffusion." (van der Laak et al. 2007, p.3216)

For the purpose of this research, we follow the definition provided in the review article by Ortt (2012). Thus, "a niche market refers to a relatively small group of customers with specific wants and demands regarding a product" (Ortt et al. 2012, p.2).

2.1.3.NICHE APPLICATION

"[N]iche application is defined as the combination of a specialized version of a product category and its matching small group of customers." (Trevino Barbosa et al. 2011, p.8) For the scope of the current thesis, we will be following the definition in the seminal paper by Ortt et al. (2013, p.2), i.e. "[a] niche application refers to relatively small group of customers with specific wants and needs regarding a product."

2.1.4.SYNTHESIS OF TERMINOLOGY

In conclusion, *niche market* and *niche application* are used interchangeably in the literature. For the scope of this research they refer to the same concept that necessarily entails: a small group of customers, which have specific wants and needs which are met by a specialized version of a product category. Perhaps, niche application is used when the product application is a proxy for explaining the customer segment, and niche market for the inverse situation, i.e. the customer segment drives the product characteristics. In reality, the two are arguably influencing one another and it becomes a chicken-and-egg dilemma to decide which one explains the other.

2.2. PATTERN OF DEVELOPMENT AND DIFFUSION

Figure 1 presents the three phases in the development and diffusion process of radically new technologies, as originally described by Ortt and Schoormans (2004): innovation, adaptation and stabilization phase. These are defined based on three hallmarks: invention, first market introduction, and market stabilization or alternatively large-scale diffusion. Firstly the hallmarks are defined, and thereafter the different phases.

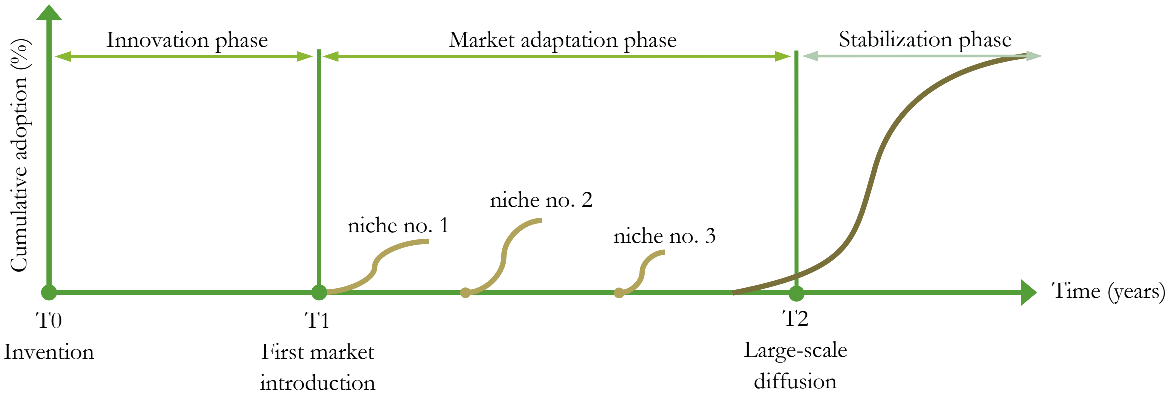


Figure 1: The pattern of development and diffusion of radically new high-tech products (based on Ortt et al. 2013; adapted from Ortt & Schoormans 2004)

The invention hallmark represents the first demonstration of the technological principle, and thus must entail the materialization of the invention. The hallmark corresponding to time T1 from Figure 1 is defined as the earliest documented introduction of the technology in the market. While this usually entails a commercial application, the reader is advised to note that while military technology is sold to governments –therefore not commercial– this instance would still constitute a market introduction; pilot projects or the mere demonstration of the technology does not (adapted from Ortt & Schoormans 2004). Lastly, the large-scale diffusion hallmark corresponds to the period when the diffusion significantly took off (Ortt & Schoormans 2004), or when "a standard product [was] produced in an industrial production process and large-scale diffusion starts" (Ortt et al. 2013, p.3).

With the hallmarks defined, it remains to explain the different phases. The first of which –innovation– corresponds to the period between the invention and first market introduction hallmarks. Typically, during this stage, the technology is available in a rudimentary form, and it is gradually "transformed into a marketable 'product'" (Ortt & Schoormans 2004, p.296). The second phase –market adaptation– is situated between the hallmarks corresponding to T1 and T2 from Figure 1. This stage is characterized by "an erratic process of diffusion […with] periodic introduction, decline and re-introduction of multiple products in multiple small-scale applications" (p.297). Some of the companies active during this stage may die off as a result of the failed market introductions and the intense competition. Lastly, market stabilization begins when the diffusion significantly takes-off and ends with the substitution of the technology. This stage is typically characterized by the S-curve referred to under Chapter 1.

2.3. STRATEGIC NICHES

"Niche markets can be further subdivided using the stage of the technology life cycle in which they emerge." (Ortt 2012, p.2) In this respect, the focus is on the adaptation phase – see Figure 1– "which begins after the first application and ends when a standard product is produced in an industrial production process and large-scale diffusion starts" (Ortt et al. 2013, p.3).

The research exclusively investigates into market niches that emerge "prior to industrial production and large-scale diffusion of a radically new technology in a mass market" (Ortt 2012, p.2), henceforth referred to as *strategic niches* (Ortt & Suprapto 2011). *Mature niches*, which emerge after large-scale diffusion, are not investigated.

The study also rules out *technological niches*, which precede market niches. In technological niches the artefacts are merely experiments or pilot projects (Weber et al. 1999), rather than products (or services) introduced in the market. Furthermore, technological niches are semi-controlled societal experiments (Hoogma 2000) which purposefully "protect new technologies against harsh market selection" (Weber et al. 1999, p.16), rather than taking regular market transactions for granted (Weber et al. 1999, p.17).

Thus, the study rules out from the investigation both niches that emerge too late – i.e. mature markets – or too early – i.e. prior to the market introduction, such as technological niches. The focus is exclusively on strategic niches. Figure 2 depicts the period of emergence for the different types of niches described in the literature, and presented above.

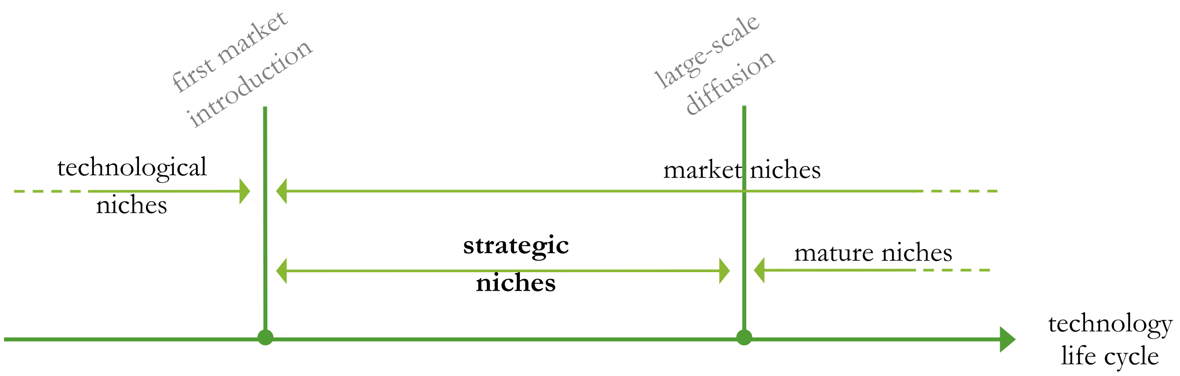


Figure 2: Timeline for the emergence of technological, strategic and mature niches

Technological niches may co-exist with strategic niches, but may equally develop into market niches (Weber et al. 1999). In this sense, the reader is advised to note that Figure 2 indicates only the timeframe for the emergence of the respective niches; not the actual span of time in which these niches may remain active.

2.4. NICHE STRATEGIES

The literature notes that "[t]here can be a strategy for each product or service, and an overall strategy for the organization" (Thompson 1993, p.2; as quoted by Hoogma 2000, p.19). Following Hoogma (2000), the focus of this research is on product strategies of various actors, and not on organizational strategies. This focus allows the tracking of various radically new products pertaining to the same technology over multiple strategic niches and initiated by different organizations.

2.4.1.ASSUMPTIONS OF THE MODEL BY ORTT ET AL. (2013)

The investigation into the assumptions of the model will focus both on explicit assumptions, but also implicit.

EXPLICIT ASSUMPTIONS

The explicit assumptions of the model are presented in the following couple of pages. The structure of the sub-section is as follows. Firstly, a paragraph will summarize the assumption(s). Next, literal extracts from the seminal paper may be presented; they are indented towards the right-hand side of the page to distinguish them clearly from the rest of the text. Readers who are very familiar with the article may skip these extracts. Lastly, at times, a figure is used to synthesize the key points.

Based on the assumption that "[e]arly niches appear when development, production or large-scale diffusion and use of a new high-tech product is hampered" (Ortt et al. 2013, p.3), the model distinguishes six core factors which are a prerequisite for large-scale diffusion:

> “The first layer of six factors […] represents the core technological and market system that is required for large scale diffusion. […] Each of these core factors needs to be in place in order to enable large-scale diffusion to occur. When one or more hampers this process, then a particular niche strategy is required.” (Ortt et al. 2013, p.5)

As the authors note “[i]f one of the core factors is missing, it is still not clear which specific niche strategy should be adopted.” (Ortt et al. 2013, p.5) In this respect, the contextual factors become a necessary prerequisite for choosing a niche strategy.

> “The second layer of factors […] referred to as influencing factors, contains contextual factors that explain why problems in the core system may emerge. […] Our [i.e. Ortt et al. (2013)] line of reasoning is that the choice for specific niche strategies requires a combination of factors. If one of the core factors is missing, it is still not clear which specific niche strategy should be adopted.” (p.5)

The combination of a core factor and the influencing – or contextual – factor represents a market situation.

> “We combine the core system and the contextual factors to create thirty-six possible market situations requiring niche strategies. Each of these market situations refers to a particular factor in the market environment that affects a particular factor in the core market system and thereby prevents large-scale diffusion.” (Ortt et al. 2013, p.9)

In theory, a total 36 market situations are possible. However, in practice, only 21 market situations were found as relevant.

> “[I]n practice, not all combinations are relevant as certain influencing [i.e. contextual] factors do not affect certain core factors.” (Ortt et al. 2013, p.6)

On the basis of the market situations investigated, the authors found “ten basic niche strategies, most of which are applicable in multiple situations.” (Ortt et al. 2013, p.6) The complete rationale behind choosing a niche strategy is described in the extract below:

> “[T]o assess which niche strategy is appropriate, knowledge is required of the core factors and the influencing factors. […] For each relevant combination of factors we […] identify which niche strategies can circumvent the barriers[;]” (Ortt et al. 2013, p.6) “and then choose a niche strategy that fits the market situation” (p.5)

Figure 3 visually depicts the selection of niche strategy(ies) on the basis of the market situation, i.e. the combination of a core and a contextual factor.

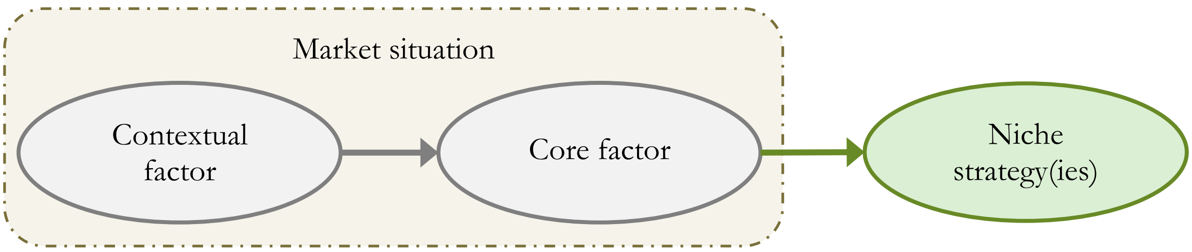


Figure 3: Selection of niche strategy(ies) on the basis of the market situation (adapted from Ortt & Suprapto 2011; Ortt et al. 2013)

An important note to be made is that “the twelve factor model allows managers, to assess the specific market situation and select one or more niche strategies” (Ortt et al. 2013, p.9), not necessarily a single one. Nonetheless, the niche strategy must be chosen such that it fits the market situation.

Equally important is the insight that "[a] niche strategy is just one option" (Ortt et al. 2013, p.9). If one of the core factors is missing, and large scale diffusion is hampered as a result, then managers can also decide not to introduce the product at all, as for instance a wait-and-see strategy, in which the pioneer of a technology purposefully opts to become a follower (see Ortt et al. 2007). Section 2.5 will detail further on these three strategic options.

IMPLICIT ASSUMPTIONS

Firstly, according to examples and explanations provided in the article by Ortt et al. (2013), a particular niche strategy is selected on the basis of a single market situation – i.e. a combination of a core and contextual factor. However, in practice there may be several core factors missing. Since each market situation is defined by the combination of a core factor and a contextual factor, this would mean that there are at least as many market situations as the number of missing core factors. The model does not explicitly mention how to select one or more niche strategies – for the same radically new high-tech product – when there are several market situations present.

Secondly, the model is by nature static. The assessment of the market situation is done at one moment in time and there is no explanation of the influence (1) of niche strategies on the market situation, or (2) of the core factor on the contextual factor. The only explicit links were summarized in Figure 3. In the concluding paragraphs of the article, it is mentioned that "[s]ome of the niche strategies […] are a combination of circumventing and creating" (Ortt et al. 2013, p.10), but "[f]urther research is required to better understand how the ten different niche strategies can be used to create new markets" (p.10), i.e. remove core factors and/or contextual factors.

Thirdly, given that the absence of the core factors is a quintessential condition before a high-tech product can be introduced – and potentially diffuse – in a mass market, the model implicitly assumes that any attempt to introduce such a product in a mass market when at least one core factor is in place is futile. Another literature stream – Functions of Innovation Systems (FIS) – on the other hand considers that the very introduction of the product is quintessential for creating space for a mass market. While the two views are not in anti-thesis, the reader may note that the model of niche strategies takes a barrier-driven approach, while FIS looks at potential barriers as opportunities for change.

Fourthly, some strategic choices available to managers – i.e. wait-and-see, introduce in niche market, introduce in mass market – are more relevant than others depending on the number of core factors in place. For instance the wait-and-see choice is a strong candidate when all core factors are hampering large-scale diffusion. At the other spectrum a mass market is a strong candidate when all core factors are absent. For the scope of the current research the interest remains in market situations where there are a moderate number of – at least one core – factors hampering large-scale diffusion, which would favour the introduction of the product in a niche market.

Lastly, while some barriers may be more important than others, the model does not make this distinction. For instance the availability of complementary products and services –such as a refuelling infrastructure for electric or hydrogen vehicles– is more important than the availability of a production system. The capital costs of the former arguably exceed that of the latter.

2.4.2. CLASSIFICATION OF CORE FACTORS

For the definitions of the core and contextual factors, as presented by Ortt et al. (2013), please refer to Appendix 1: Definitions by Ortt et al. (2013). The remainder of the section will present the classification of core factors, based on a review of the literature on the topic. Figure 4 presents the outcomes.

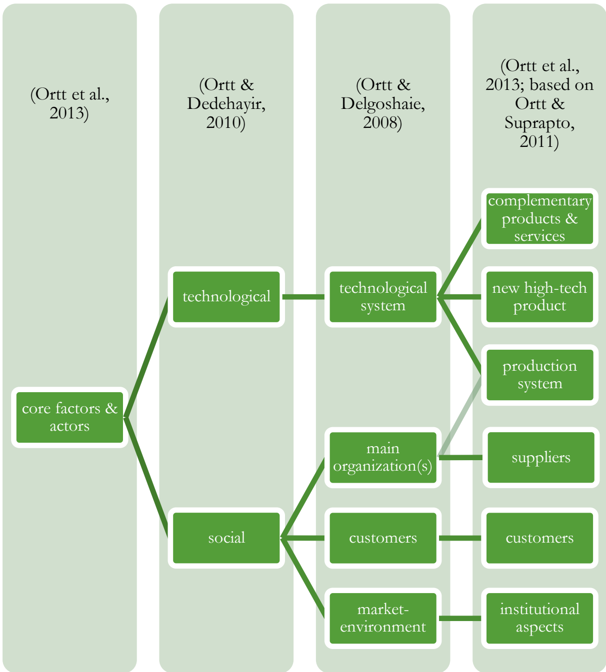


Figure 4: Classification hierarchy of core factors & actors hampering large-scale diffusion for the case of radically new high-tech products (based on Ortt & Delgoshaie 2008; Ortt & Dedehayir 2010; Ortt & Suprapto 2011; Ortt et al. 2013)

2.4.3.REVISING THE LIST OF NICHE STRATEGIES

For the descriptions of niche strategies, as presented by Ortt et al. (2013), please refer to Appendix 1: Definitions by Ortt et al. (2013).

According to Figure 4, it may be observed that the 'redesign' niche strategy corresponds to market situations entailing technological core factors, but also social core factors. Therefore, for ease of referral, the strategy will be split into 'technological redesign' niche strategy and 'social redesign' niche strategy. Upon reflection, by splitting the 'redesign' niche strategy into these two constituencies, the number of market situation to which each corresponds was brought down to a number closer to the other niche strategies hypothesised by Ortt et al. (2013). Thus, using the definitions of the authors, the market situations for each of the two niche strategies would be described as follows:

'technological redesign' niche strategy

"Knowledge of the technology is lacking and that affects the availability of the product or the production system and that in turn affects the availability of the product for a reasonable price.
Resources for the product or the production are lacking or very expensive and that affects the product's price." (Ortt et al. 2013, p.9)

'social redesign' niche strategy

Knowledge of the application of the product is missing or socio cultural aspects affect the availability of appropriate institutional aspects (laws, rules and standards) and thereby hamper diffusion.
Socio-cultural aspects affect the availability of suppliers or customers." (Ortt et al. 2013, p.9)

The revised list of niche strategies is as follows:

Table II: Revised list of niche strategies

1. Demo, experiment & develop n.s.
2. Top n.s.
3. Subsidized n.s
4. i. Technological redesign n.s.
4. ii. Social redesign n.s.
5. Stand-alone n.s.
6. Hybridization n.s.
7. Educate n.s.
8. Geographic n.s.
9. Lead user n.s.
10. Explore multiple markets n.s.

2.4.4.MATCHING NICHE STRATEGY TO MARKET SITUATION

Using the revised list of niche strategies –see Table II– and the descriptions of the market situation provided by Ortt et al. (2013), each niche strategy can be traced back to the market situation on the basis of which it may arise, as presented under Table III.

Table III: Matching market situation to niche strategy

	new high-tech product	production system	complementary products & services	suppliers	customers	institutional aspects
knowledge technology	1 2 3 4i	2 3 4i	5 6	7	7	8
knowledge application				9	9 10	4ii 8
resources	2 3 4i 8	2 3 4i	6 8			
socio-cultural				4ii 8 9	4ii 8 9	4ii 8
macro-economic				8 9	8 9	8
accidents / events				9	9	8

The table should be read as follows: by intersecting the contextual factor from the left-hand column with the core factor from the upper row, the market situation is given; at this intersection, the numbers listed in the column correspond to the different niche strategies, as indexed under Table II. For instance, intersecting the contextual factor 'knowledge of technology' with the core factor 'new high-tech product' yields four potential niche strategies that may arise: 'demo, experiment & develop' niche strategy, 'top' niche strategy, 'subsidized' niche strategy, and lastly 'technological redesign' niche strategy.

2.5. STRATEGIC OPTIONS

Ortt et al. (2013, p.9) note that "after the invention of a new technological principle and after the development of a new high-tech product on the basis of that invention, managers have several strategic options." They may choose to introduce the product or not.

For the case in which the product is introduced, managers can opt between a mass market introduction and niche market introduction. The former is considered a possibility provided that "all the core technological and market factors are in place and do not hamper large-scale diffusion, and if none of the contextual factors could block this large-scale diffusion" (Ortt et al. 2013, p.10). When there are remaining barriers, then a niche strategy can be implemented in order to circumvent the market situation (Ortt et al. 2013).

A wait-and-see strategy might be appropriate when there are many factors hampering large-scale diffusion. Therefore, it would make sense to wait for external factors or other market players to influence the dynamics of the barriers.

3. TOWARDS A DEFINITION OF A SEQUENCE OF NICHE STRATEGIES

3.1. DEFINING NICHE STRATEGIES

In the paper by Ortt et al. (2013) there is no explicit definition of a 'niche strategy'. The current sub-section aims to address this gap and arrive at a definition. The methodology is as follows: firstly, any niche strategy should follow the general definition of strategy; secondly, a literature search on Google Scholar is used to uncover the already available definitions for niche – or niche market/marketing – strategies; and lastly, the definition of niche strategy for the scope of the current research should reflect the entirety of the 10 generic niche strategies reported by Ortt et al. (2013). Table IV presents the search procedure for the literature review.

Table IV: Literature search procedure for defining the concept of 'niche strategy'

Concept	Search procedure	Comments
strategy	A very brief selection of seminal works on the topic of strategy and/or marketing: Mintzberg et al. (1998), Porter (1980), Porter (1996), Kotler (2000).	Additional works by Porter (see 1998b; 1998a) are referred to, but merely as directions for interested readers.
niche strategy	Query on Google Scholar using the phases: • *~define "niche strategy" innovation* • *~define "niche * strategy" innovation* The articles were sorted using the query function 'sort by relevance'. Furthermore, only those works more recent than the year 2000 were included in the search.	Only the first 20 articles from each search were considered. There was an overlap of eight results. Thus, 32 unique results were considered. From the selected sample of articles, 15 were found to contain explicit definitions of niche strategies.

The following paragraphs explain the choices presented in Table IV. Firstly, the body of literature on the topic of strategy formulation is extensive and comprising of many schools of thought (Mintzberg et al. 1998). Thus, to arrive at a useful definition of strategy, a good starting point would be to start from the school – or schools for that matter – of taught that is most proximate to the model proposed by Ortt et al. (2013). Failing to do so would risk directing the search towards unworkable definitions. The work by Mintzberg et al. (1998) represents a very practical point of departure, given that it quickly directs the search towards the 'positioning school' of strategy, in which Porter's (1980) books on "Competitive Strategy" and later "Competitive Advantage"(Porter 1998a) represent the foundation and "a set of concepts on which to build [upon]" (Mintzberg et al. 1998, p.100). The search was by all measures very brief, given that the single interest was to uncover a generic, broadly accepted and workable definition of strategy; one in which the work of Ortt et al. (2013) would fit.

Secondly, regarding the search on Google Scholar, several aspects must be clarified: starting with the search terms and concluding with motivating the choices for the selection of some articles over others. Concerning the symbols and operators, it is worthwhile to mention that the query on Google Scholar automatically includes word stemming, which is "a technique to search on the stem or root of a word that can have multiple endings" (Google Guide 2012a). This means that searching for the term "[~]define" will automatically include words such as 'definition', 'defined', etc. The operator "~" indicates the search will also include synonyms of the respective word; and does not exclude stemming. The symbols " " indicate the search will consider the exact phrase enclosed between quotation marks. Lastly, the symbol ' * ' indicates that it may be replaced by one or several words in the actual search results (Google Guide 2012b).

Regarding the choice for the specific key terms, the objective was to maximize the chances of arriving at those articles that would define a niche strategy in explicit terms. The operator ' * ' was used since some authors prefer the use of the term niche market strategy or niche marketing strategy over the former. The last key term – "innovation" – was employed to narrow down the search to only those articles discussing niche strategies relevant in the context of diffusion of innovation. The articles were selected to have been published later than the year 2000, such that they may reflect more recent works that Kotler (2000). The cut-off point of 20 selected works was chosen, since for both queries the relevance of the search decreased around this number. For instance, for the query *~define "niche strategy" innovation* the 20th result – i.e. query hit – mentioned the phrase 'niche strategy' merely once throughout the entire article and there was no explicit definition given.

The remainder of the sub-sections will present the results of the literature search from Table IV, while the last sub-section will synthesise the findings to accommodate the 10 generic niche strategies hypothesised by Ortt et al. (2013).

3.1.1.STRATEGY IN THE VIEW OF THE POSITIONING SCHOOL

According to Porter (1980, p.24), "competitive strategy is a combination of the ends (goals) for which the firm is striving and the means (policies) by which it is seeking to get there." Kotler (2000, p.40) describes it more simply as "a game plan for achieving long-term objectives."

With respect to the views on strategy formulation, the research is most proximate to the *positioning school* (see Mintzberg et al. 1998). From this perspective, Porter (1996, p.68) defines strategy as "the creation of a unique and valuable position, involving a different set of activities". The key to strategic positioning means the company "performs different activities from rivals' or performs similar activities in different ways" (Porter 1996, p.62).

Mintzberg et al. (1998) attribute to the *positioning school* a major emphasis on analysis and calculation. The role of the strategic analyses is to support the process of strategy formulation; and they allow the manager or consultant to match the right strategy – from a limited collection of generic strategies (see Porter 1998b; Porter 1998a) – to the conditions at hand (Mintzberg et al. 1998). Figure 5 presents the definition of a strategy, primarily following Mintzberg et al. (1998).

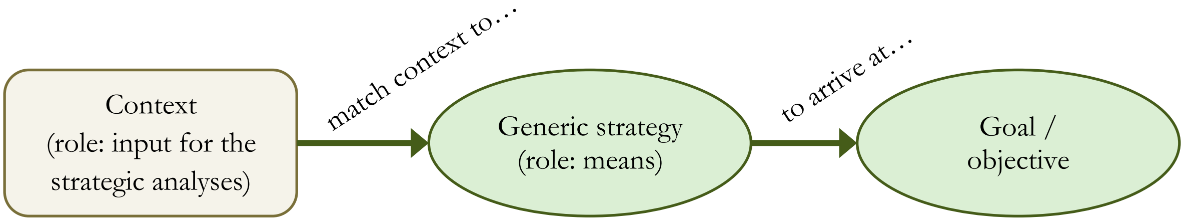


Figure 5: A generic definition of strategy

3.1.2.NICHE STRATEGY AS EXPLICTLY DEFINED IN THE LITERATURE

This sub-section presents the results of the literature review on the topic of niche – or niche market / marketing – strategies. From the selected sample of articles, 15 were found to contain explicit definitions of niche strategies. The industries were diverse, ranging from across industries (see Iansiti & Levien 2002; Iansiti & Levien 2004) to a single industry (Schaltegger 2002); or from high-tech industries – such as automotive (see Rhee et al. 2006), transport, communication and others (see Debruyne et al. 2002) to those typically regarded as low-tech – for instance rural entrepreneurship in Portugal (see Dinis 2006). The papers which did not focus on high-tech industries were not excluded from the selected sample of articles, provided that they still accounted for technological uncertainty or innovation. For instance, the series of papers by Parrish et al. (2006a; 2006b) focussing on the apparel and textile industry – which would typically not fall under the umbrella of high-tech industries – depicted a well-structured literature review, and featuring authors such as Kotler or Porter. In the view of the author, their literature review findings remain applicable to industries eliciting greater technological and market uncertainty, such as automotive.

The majority of the articles associated the concept of niche strategy with either a differentiation strategy (Hagen et al. 2012) or a focussed strategy (Solberg & Durrieu 2008); or both. The foundation for these views lies in Porter's (1998b) competitive strategies, or how one paper notes "[t]hree out of the four generic competitive strategies recommended by Porter […] result in the creation of niche markets, namely the differentiation strategy, the cost focus strategy and the differentiation focus strategy. […] In a differentiation strategy, a firm selects one or more attributes of a good that many buyers perceive to be important, and uniquely positions itself to meet those needs […]. In its focus strategies, a firm chooses a narrow competitive scope within an industry, and it 'tailors its strategy to serving them (segments) to the exclusion of others' […]" (Tisdell & Seidl 2004, p.124). Some authors explicitly preferred to use alternative terms for niche strategies. For instance, the terms used for a niche strategy with a very clear customer focus were: targeting strategy (see Debruyne et al. 2002, p.162; based on Porter 1980), focus strategy (Solberg & Durrieu 2008, p.8; based on Porter 1980), or even niche focus strategy (Aspelund et al. 2007).

There were some outliers, which used the concept in a slightly altered manner. For example, for Dziura (2001) the niche innovation strategy was actually an 'opportunist' strategy: "[t]here is always the possibility that an entrepreneur will identify some new opportunity in the rapidly changing market, which may not require any in-house R&D, or complex design, but will enable him to prosper by finding an important 'niche', and providing a product or service which consumers need" (Dziura 2001, p.624). Another example is the paper by Shum and Watanabe (2007) on the topic of photovoltaic technology in Japan and the United States. Stemming from the field of Strategic Niche Management, they placed more emphasis on how the niche strategy "will necessitate a particular system design and production-learning economy which must match the learning characteristic of the underlying institutional structure of production" (Shum & Watanabe 2007, p.1188).

Among the definitions presented in the papers, the one put forward by Parrish et al. (2006a; 2006b) was eventually considered: "[f]rom an overall firm strategy perspective, a niche market strategy is defined as 'an emphasis on a particular need, or geographic, demographic or product segment'"(Teplensky et al., 1993; as cited by Parrish et al. 2006a, p.695). On one hand, in line with the majority of the papers from the literature review, it includes the aspect of 'focus'. On the other hand the definition is generic enough to match both the earlier definition of a strategy, and offers sufficient room for adaptation to accommodate also the 10 generic niche strategies.

In the view of the author the 10 generic niche strategies hypothesised by Ortt et al. (2013) do not explicitly contain the aspect of 'differentiation', which had been formerly highlighted in the literature. In fairness, nor do the 10 generic niche strategies exclude this aspect. Hence, for the scope of this research it has been decided that 'differentiation from competitors' should not be explicitly included in the definition of a niche strategy. Nevertheless, the phrasing of the definition should not exclude this either.

Parrish et al. (2006a; 2006b) also make an interesting distinction between a niche market strategy and niche product strategy. In their view, the niche market strategy represents "a pull marketing approach in which the company identifies a potential market segment and then develops or refines a product for that particular market [, whereas a] niche product strategy is characterized as a push marketing approach in which the company develops a product and then looks for a suitable market segment for that particular product" (Parrish et al. 2006a, p.430).

Both the pull and the push marketing approach are compatible with the niche strategies from the generic list by Ortt et al. (2013). For instance, the 'top' niche strategy resembles more to a pull approach – i.e. niche market strategy – given that the products are made to order for the specific requirements of the market niche. At the other spectrum, a 'geographic' niche strategy resembles more to a push marketing approach – i.e. niche product strategy – given that a favourable market for the (almost) definitive product is sought after.

3.1.3.NICHE STRATEGIES AS DEPICTED BY ORTT ET AL. (2013)

Firstly, it's important to re-iterate an idea from section 2.3 whereby the focus of this research lies on strategic niches. In the words of Ortt et al. (2013, p.3) "the focus is on the adaptation phase" –referring to the market adaptation from the model developed initially by Ortt & Schoormans (2004) and described at more length under section 2.2. Thus, the definition of niche strategies should restrict the timeframe for the emergence of the corresponding market niches to the adaptation phase; alternatively to the timeframe reserved to strategic niches, as presented under section 2.3.

Secondly, if we are to accept the above implication, it follows that any niche strategy should result in revenue to be derived as a result of implementing it. In absence of this requirement, technological niches such as research & development experiments or pilot projects could be potentially considered under 'demo, experiment and develop' niche strategy. As illustrated under section 2.3 that is not the case.

Thirdly, the objective of the niche strategies can be derived directly from the work by Ortt et al. (2013), in the sense that initially any niche strategy can be seen as the means through which a company can respond to a market situation with the objective of circumventing the barriers hampering large-scale diffusion present in that market situation.

Lastly, the niche strategies presented in the paper by Ortt et al. (2013), appear to be stacked on a continuum between 'develop a marketable product application' and 'market the already available product (application)' within the existing regime. Figure 6 presents the categorization of niche strategies according to core issue at which they are aimed at.

Develop a marketable product application		Market the already available product (application)
1. Demo n.s.	4. i. Technological redesign n.s.	2. Top n.s.
4. ii. Social redesign n.s.	5. Stand-alone n.s	3. Subsidized n.s.
10. Explore multiple markets n.s.	6. Hybridization n.s.	7. Educate n.s.
	9. Lead user n.s.	8. Geographic n.s.

Figure 6: Core issue addressed by niche strategies (n.s.)

Consider the niche strategies at the far left of the continuum. "As part of the strategy [demo, experiment and develop'] experimenting with the product is important to develop the product further" (Ortt et al. 2013, p.6) 'Social redesign' must re-engineer the product in a societally-accepted or regulatory-compliant version. 'Explore multiple markets' deliberately alters the product application in search of the befitting customer segment.

Now, take the niche strategies at the far right of the continuum. These strategies do not require any further product modifications; but rather further improvements in the actual marketing. 'Top' and 'subsidized' both target the prohibitive price, and essentially they look at supplying the already-developed product to a particular customer segment; either because of the willingness-to-pay, or the societal benefit respectively. 'Educate' and 'geographic' take the existing product and either seek to educate consumers of its benefits or find a market favourable enough to eschew such efforts altogether.

Roughly in the middle of the continuum stand those that elicit characteristics of both extremes. For instance 'technological redesign' and 'stand-alone' niche strategies entail both the redesign of the product into a market application –e.g. a simpler version, respectively the conversion to the requirements of a dedicated infrastructure– and the corresponding marketing efforts –e.g. commanding a lower price point, respectively sell the product to a niche from the incumbent regime. 'Hybridization' requires the development of the adaptor, and once again the marketing efforts to appeal to an existing niche from the incumbent regime. Lastly, "lead users […] co-develop the product and […] are willing to experiment with the [already-developed] product [once its completed]" (adapted from Ortt et al. 2013, p.9).

3.1.4.ARRIVING AT THE DEFINITION OF NICHE STRATEGY

A niche strategy represents a response to circumvent a market situation characterized by hampered large-scale diffusion, by which a company deliberately focuses on strategic niches in the effort to (1) develop a marketable product application or (2) market an already developed product in the existing regime, if and only if revenue can be derived from the market introduction.

The strategic niche referred to in the definition is characterised "from an overall firm strategy perspective, […] as 'an emphasis on a particular need, or geographic, demographic or product segment'" (Teplensky et al., 1993; as cited by Parrish et al. 2006a, p.695).

The analysis of the market context allows a company match the right strategy –from a limited collection of generic strategies (see Porter 1998b; Porter 1998a)– to the conditions at hand (Mintzberg et al. 1998). In the context of Ortt et al. (2013) the 10 generic niche strategies embody the limited collection of strategies; while the conditions at hand can be seen to represent the core and contextual factors.

3.2. CONCEPTUAL MODEL OF CURRENT RESEARCH

The following paragraph provides a short review of the literature behind the conceptual model, presented in the chronological order of developments. Kemp et al. (1998) were among the first to mention about barriers to large-scale diffusion. Ortt and Delgoshaie (2008) explain how barriers to large-scale diffusion require managers to first introduce their technologies in a market niche. Ortt and Suprapto (2011), building upon the work of Ortt and Delgoshaie (2008), bring one important contribution in further refining the barriers, by grouping them in two groups of factors: 'layer 2' – representing "causes of incomplete socio-tech[nical] systems" (Ortt & Suprapto 2011, p.13) and 'layer 1' – "factors required in a complete socio-tech[nical] system" (Ortt & Suprapto 2011, p.13) or alternatively referred to as "market factors" (Ortt & Suprapto 2011, p.15). In hindsight this is a very elegant solution "because one part of the model can be used to explain the emergence of the adaptation phase [see section 2.2], while the other to indicate the type of niche strategy" (Ortt & Suprapto 2011, p.16). Lastly, Ortt et al. (2013) bring the last refinement to the model by adding one more factor to each of the formerly defined groups of factors. They are also the first to hypothesize the different market scenarios, as a pair of the type *contextual factor* → *core factor*. The niche strategy is chosen such that it fits the market scenario.

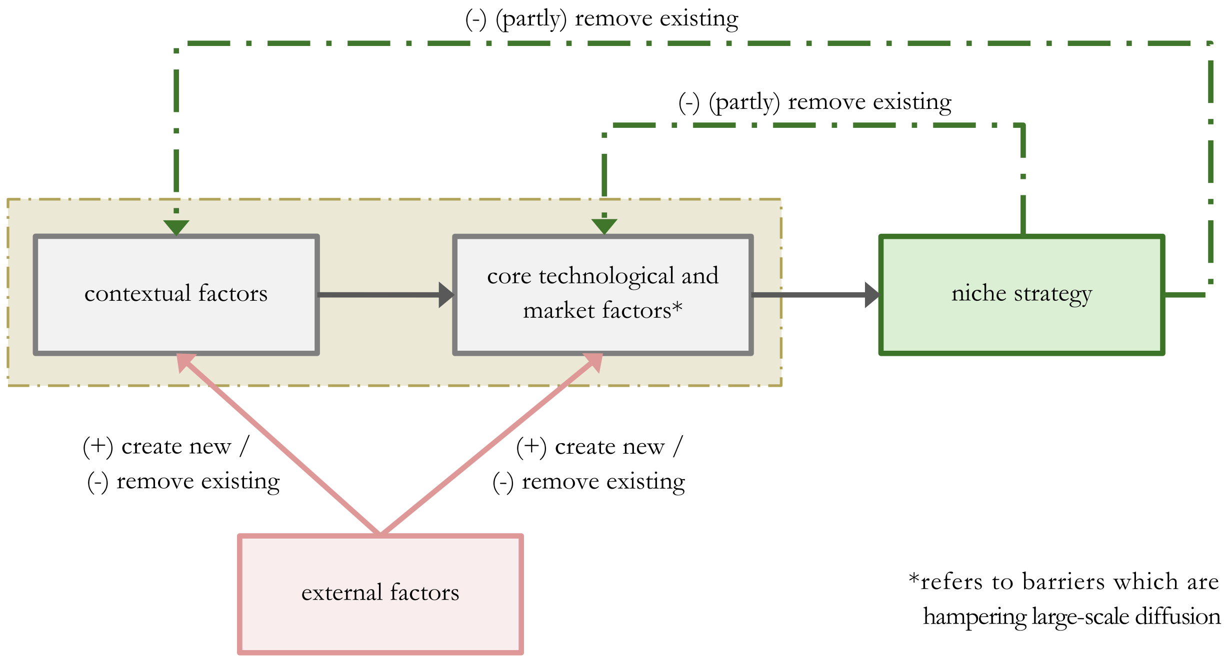


Figure 7: Conceptual model

The current paragraph shortly explains the model from Figure 7. The core factor hampers the large-scale diffusion of the radically new high-tech product, which means that the product can only be introduced in a niche market. Since core factors alone are not enough to choose a niche strategy, identifying the contextual factors is imperative. Once the contextual factor(s) and the core factor(s) are known, the niche strategy can be selected. After a product is introduced in a niche market, the contextual and/or core factor can be altered on the basis of two variables: niche strategies and external factors.

The concept of 'external factor' refers to any factor / phenomenon that can influence the 'core' and/or 'contextual factors', as represented under Figure 7 by the solid light red arrow departing from the concept.

In terms of the influence of niche strategies, Ortt et al. (2013) hypothesised that –in addition to the circumventing effect over a barrier– some niche strategies can help in (partially) removing the hindering effect of the barriers. This latter effect is demarcated by the dotted dark green arrows under Figure 7, and represents a relationship that has yet to be tested by the current body of literature. Furthermore, it would be interesting to observe whether the effect of niche strategies would be to also give rise to new 'core' or 'contextual factors'. Currently, the literature does not hint at this possibility, but it is logically conceivable given that external factors were demonstrated to elicit this influence.

3.3. DEFINING SEQUENCES OF NICHE STRATEGIES

Figure 7 exemplifies a generic sequence of three niche strategies. Sub-sections 3.3.1 will detail on the key criterion that distinguishes between series of niche strategies and sequences. This relates to the arrow featured under Figure 8 labelled with "logically followed by". Continuing to 3.3.2

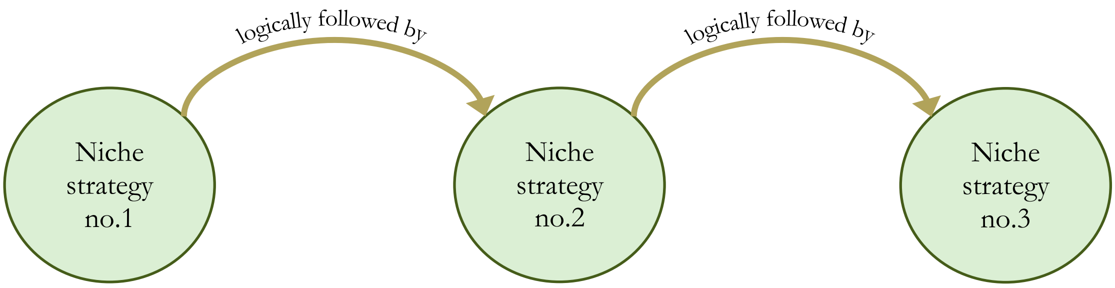


Figure 8: Generic example for a sequence of three niche strategies

3.3.1.THE KEY DIFFERENCE BETWEEN SERIES OF NICHE STRATEGIES AND SEQUENCES

For the scope of this research, the distinction of (Hoogma 2000; based on Mintzberg & Waters 1985) between deliberate and emergent strategies –recall from section 1.1– is relevant when defining the different exhaustive time series of niche strategies that may occur:

- *series of niche strategies*: provided there is merely an order in time. In other words, niche strategies simply follow one another during the pattern of development and diffusion.
- *emergent sequence of niche strategies*: provided that in addition to the time series there is also an emergent logic between the niche strategies. For instance, the impact –or lack thereof– of the first niche strategy on the barriers is taken into account by the next actors wishing to introduce the product in a strategic niche. As a side note, the logic need not necessarily relate to barriers.
- *deliberate sequence of niche strategies*: provided that in addition to the time series there is also an up-front deliberate logic that may be explained. In this sense, the central actor pursues a deliberate sequence, which is known in advance to the first introduction via a niche strategy.

It remains to be defined what constitutes a logical series as opposed to 'non-logical' series of niche strategies. Given the exploratory nature of the research, the logic will not be defined up-front; rather, it will be an outcome of the research.

As an example, Figure 9 considers a generic sequence of two niche strategies. Specifically for this hypothetical situation, the rationale could arguably be the progressive removal of the barriers to large-scale diffusion.

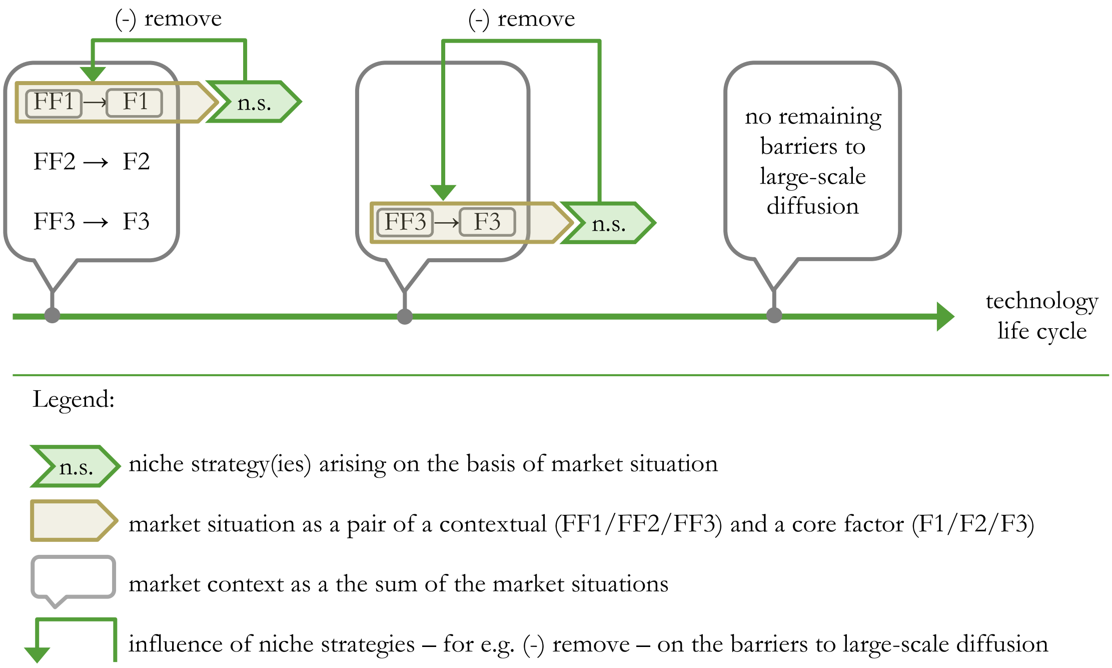


Figure 9: An example of a sequence of two niche strategies

3.3.2.ASSUMPTIONS OF THE DEFINITION OF SEQUENCES OF NICHE STRATEGIES

The definition is built on a number of assumptions, which will be detailed upon in this section. Where applicable, the implications stemming from the assumptions will be presented as well.

The first assumption entails that for any sequence of niche strategies to exist, the market adaptation phase corresponding to the radically new high-tech product must display at least two subsequent niche strategies; not necessarily different from one another. An example of this situation can be found in the case ABS, when the technology was subsequently introduced via the same niche strategies in aviation and thereafter in automotive.

Secondly, some words are in order with respect to the temporality of series, or sequences. Niche strategies which are employed for the same product introduction – or product demonstration – at more or less the same moment in time – i.e. a matter of years – are considered to be simultaneous, rather than subsequent. For instance, the dual-clutch technology was introduced in the niche market for sports cars via a geographic niche strategy – by targeting the specific demands and needs of European drivers – and an educate niche strategy – whereby the introduction of the product in sport cars increased customer knowledge with regards to the product use, actual performance and benefits. In the view of this research, these niche strategies should not be regarded as subsequent; rather they were simultaneous.

Please note that several niche strategies may be coupled at once, and together be part of the same sequence; for instance using 'top' and 'subsidized' niche strategy simultaneously, followed by 'geographic' niche strategy.

Thirdly, as mentioned in an earlier section, niche strategies have been hypothesised to remove barriers to large-scale diffusion. Should it be proven true, then this influence would contain –one of– the mechanisms by which sequences of niche strategies can prove effective, i.e. realize their scope, in the progressive removal of the barriers. However, this need not happen solely due to niche strategies. For instance, in Figure 9 the pair of contextual and core factors "FF2 → F2" disappeared on the basis of other factors than niche strategies.

3.3.3.EXPLORING THE LOGIC BEHIND SEQUENCE OF NICHE STRATEGIES

Figure 10 explores the potential logic behind a sequence of niche strategies. The first categorization is based on the former typology of rationales: emergent and deliberate. Moving down a branch, for each of type of logic, the inherent reason for pursuing the sequence are posited to be the exploitation or the exploration of the market context.

The current sub-section is structured as follows. Firstly, it is explained from which field of literature were the ideas of exploitation and exploration derived, and most importantly why that field would be a good choice for branching down the categorization. Secondly, the two constructs are explained in the context of the current research work. Lastly, some examples are given as to what to expect from each of the four emerging categories.

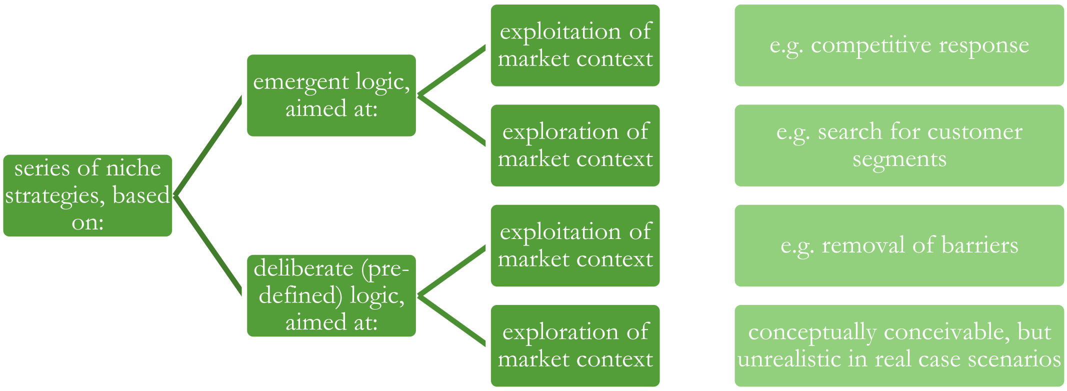


Figure 10: Classifying the potential logic behind sequences of niche strategies

The two concepts, exploration and exploitation, were adopted from the literature on entrepreneurship. The primary aim of this paragraph is to explain 'why the topic of entrepreneurship would be relevant to the typology. Following Lumpkin & Dess (1996), entrepreneurship can be boiled down to 'new entry' and figuring out which business to enter "determine[s] a firm's domain and guided its product-market relationships and resource deployments" (Lumpkin & Dess 1996, p.136). From this perspective, niche strategies and entrepreneurship are very much connected, since they entail new product introductions in new/existing markets –i.e. the "which business to enter?" aspect– and they also define the potential scope of the business –i.e. they demarcate the range of market opportunities that a company may consider entering within the prohibitive limits of the market context. Lastly, company resources and product-market relationships are characteristics elicited by the core and contextual factors; for instance: '(natural resources and) labour' and 'knowledge of the technology' are related to the concept of company resources, or product-market relationships are ingrained in the 'customers' core factor.

After concluding and explaining on why the topic of entrepreneurship is relevant to the typology, the two newly introduced constructs are to be explained. The reader is advised to note that these constructs are defined solely in the context of the current research work. In this sense they are reduced to their core meaning, which is: "[e]xploration includes things captured by terms such as search, variation, risk taking, experimentation, play, flexibility, discovery, innovation. Exploitation includes such things as refinement, choice, production, efficiency, selection, implementation, execution" (March 1991, p.71). March (1991) goes on to adapt these terms in the context of organizational learning and entrepreneurship, but for the current work the original inductive definition suffices, since collectively the are thought to offer an exhaustive range of capturing business opportunities. But the attempted categorization should be not just collectively exhaustive, but also mutually exclusive which at first glance would be problematic to argue in favour of since exploitation and exploration are not necessarily excluding one another. While this is true, they should be seen as two opposing sides of a continuum. Depending on which side of the continuum the logic is more prone to resemble, then that is the label which it will be given according to Figure 9. As March (March 1991, p.71) mentioned: "organizations make explicit and implicit choices between the two. The explicit choices are found in calculated decisions about alternative investments and competitive strategies."

With the two concepts explained, a short set of examples in the context of sequences of niche strategies should follow. To take the upper most box, an emergent sequence based on an exploitation rationale could be represented by a series of competitive responses sequenced over time and entailing product introductions via niche strategies. Conversely, a deliberate sequence using the same rationale would be counter-intuitive, since the competitive response might be hard to plan up-front; that is not to say that it cannot be expected, but the degree of variation in actors' choices would entail a large range of scenarios to be accounted for in the initial scheduling of sequences. However, a reasonable example of a deliberate sequence based on an exploitation rationale would be the up-front targeted removal of barriers. In this situation, the central actor would schedule the different market introductions and the associated niche strategies in the effort to remove or diminish the magnitude of the barriers, and this impact would act as an enabling force for the next instance of niche strategy(ies): for e.g. the 'demo, experiment and develop' would increase the knowledge of the technology, which in term would enable the actor to provide a more reliable version –though not yet completely reliable– to a 'top niche' willing to pay the premium for the associated product benefits. This would be the case for racing innovations moving to sport cars for instance.

In contrast, an emergent sequence based on an exploration rationale could be the search for better customer segments. In this situation market actors would target different customer segments via subsequent niche strategies in the pursuit of a larger/ more profitable / etc. customer segment. Although conceptually conceivable, a deliberate sequence based on the same exploration rationale is harder to imagine in a real case scenario, since actors would have to plan in advance for the variation of their exploration rationales, which even seems counter-intuitive to begin with.

3.4. EXPLAINING THE DIFFERENT SEQUENCES

The reader may find confusing the differences between sequences of: niches, niche applications, niche markets, respectively niche strategies. Thus, the aforementioned types of sequences are to be distinguished in the upcoming sub-section.

3.4.1.SEQUENCE OF NICHES

The review article by Ortt (2012) inquired explicitly into the sequences of niches described in the literature, as part of the second research question of the article. Three sequences of niches were distinguished, as described in the next three paragraphs.

The first type of sequence describes primary niche and secondary niche. The primary niche should focus on providing a unique functionality of the technology to a specific market niche. Under these circumstances, the technology is shielded from competition with established technologies, but may face competition from alternative new or emerging technologies. The secondary or subsequent niche(s) should be entered once the technology has matured enough to compete with contemporary technologies on the basis of the particular benefits of the technology (Ortt 2012; based on Adamson 2003). In conclusion, for this case, the sequence of niche refers to the introduction of the technology in subsequent market niches with substantially different degree of competition to established technologies, on the basis of the maturity of the technology.

The second type of sequence places technological niches, prior to market niches. The – sustainable – technology should be tested in an experimental environment or pilot setting, i.e. a technological niche. After sufficient alignment of the processes taking place within the niche, it may gradually expand to specific market niches where the technology is exposed to competition from other technologies (Ortt 2012; based on Schot & Geels 2008). In conclusion, for this second case, the sequence of niches refers to the introduction of the technology in subsequent niches with different degree of competition to other technologies; first experiments or pilot projects in technological niches, followed by market introduction in strategic niches. The introduction is done on the basis of the alignment of the internal niche processes: network dynamics, learning – alternatively named articulation – processes, and dynamics of expectations (Hoogma 2000). Nonetheless, since technological niches are positioned before market niches in the technology life cycle, one can argue that the introduction is also done on the basis of the maturity.

The third type of sequence is derived from the market of organic foods. It is similar to the second case, in the sense that protection from existing technologies is required; also, a gradual up-scaling unveils over time. However, contradictory to the second case, the literature supporting this sequence of niches objects towards the government's intervention to shield off competition. In conclusion, although slightly different, the third type of sequence of niches also refers to the introduction of the technology in subsequent niches with different degree of competition to other technologies.

Synthesizing the above, it follows that the literature describes sequences of niches as subsequent niches – not necessarily market niches, but also technological niches – wherein technologies are introduced in the effort to shield them off from the existing competition, on the basis of different factors – maturity, alignment of internal processes, etc. – depending on the literature stream.

3.4.2.SEQUENCE OF NICHE APPLICATIONS / MARKETS

Ortt et al. (2012) investigate into sequences of niche applications – according to the title of the article – by categorizing the market niches according to the customer groups. Their methodology entails pinpointing the different product applications of radically new technologies in niche markets. For each product application they define the customer groups according to two dimensions: on one hand they divide the groups into government-public, government-military, business and consumers; and on the other hand among these groups they distinguish between military, civil, public and private niches. Thus, they are ultimately interested to describe the types of customer groups –in niche markets– catered by the product applications of the radically new technologies.

Following the definitions from section 2.1, niche application and niche market can be used interchangeably. In conclusion, a sequence of niche applications is fundamentally the same concept as a sequence of niche markets; both terms referring to the introduction of technologies in subsequent market niches on the basis of the specific wants and needs of the small customer segments from a particular product category. In such a sequence, the customer segment may vary from one instance to the other; or the product application; or both product application and customer segment.

For the research of Ortt et al. (2012) it is more practical to use the sequence of niche applications, because they first arrive at a specific product application in a niche market and only after do they assign it to one of the types of strategic niches – i.e. the customer groups – they had formerly defined.

3.4.3.SYNTHESIS

Table V summarizes the points of comparison between the different types of sequences presented earlier.

Table V: Comparison between sequence of niches, niche applications / niche markets, and niche strategies

Sequence of niches entails:	*Sequence of niche applications / niche markets* entails:	*Sequence of niche strategies* entails:
• subsequent niches –not necessarily market niches, but also technological niches– (see below)	• subsequent market niches (see below)	• subsequent niche strategies (see below)
• starting from niches with minimum exposure to existing competition and progressively moving towards direct competition with existing technologies	• chosen on the basis of specific wants and needs of the small customer segments from a particular product category	• provided that in addition to the series in time, there is also an emergent / deliberate logic explaining the order of the niche strategies

4. METHODOLOGY

This chapter corresponds to the first research question, i.e. "What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?".

4.1. RESEARCH DESIGN

4.1.1. MULTIPLE-CASE STUDY

A multiple-case study research design was chosen for the investigation. The evidence from this particular research design, versus a single-case study, is considered more compelling and the overall study is considered more robust (Yin 2003).

4.1.2. CONSTRUCT VALIDITY

Construct validity refers to the correct establishment of operational measures for the concepts being studied. In meeting the test of construct validity, there are two distinct steps to be covered: (1) selecting the specific types of changes which the investigator will study, and (2) demonstrating that the selected measures for the changes are indeed a reflection of the type of change selected (Yin 2003).

For step (1), the specific types of changes to be investigated were presented under sections 3.2 concerning to what constitutes a change due to external factors versus that of the niche strategy; and section 3.3.2 regarding the type of rationale that the sequence of niche strategies should be able to explain. For step (2), the case report provides the argumentation for these changes.

4.1.3. INTERNAL VALIDITY

According to Yin (2003, p.36) "internal validity is only a concern for causal (or explanatory) case studies […] this logic is inapplicable to descriptive or exploratory studies". Given the exploratory nature of this research, further elaboration on the topic of internal validity is not required.

4.1.4. EXTERNAL VALIDITY

External validity refers to the degree to which a study's outcomes are generalizable beyond the immediate case study. Case studies rely on analytical generalisation, rather than statistical generalisation as in the case of survey research. In the process of analytical generalisation, the researcher "is striving to generalize a particular set of results to some broader theory" (Yin 2003, p.37).

For this research, the broader theory is: (1) the conceptual model from section 3.2, (2) the model of sequences of niche strategies as presented under section 3.3, and (3) the typology of the different rationales for sequences of niche strategies from section 3.3.2. Thus, in concluding upon the research results, these three above aspects need to be included.

4.1.5. RELIABILITY

For reliability purposes, each case study should be completed using the case study protocol, which can be found under sub-chapter 4.4. "The protocol is a major way of increasing the reliability of case study research and is intended to guide the investigator in carrying out the data collection from a single-case study […] even if the single case is one of several in a multiple-case study" (Yin 2003, p.67).

The case study protocol should contain the overview of the case study project, data collection procedures, the case study questions, and a guide for the case study report (adapted from Yin 2003). Please note that the overview of the project is considered to have been provided in the earlier chapters of this thesis; thus, it will not be included. The other aspects are to be found.

Lastly, the final element contributing towards increasing the reliability of the research relates to the reporting of the data collection documents under Appendix 4: Case Repository. The reader is advised to note that the documents contain literal quotations from the sources, therefore eliminating any interpretation of the core data by the author.

4.2. UNIT OF ANALYSIS & UNIT OF OBSERVATION

The unit of analysis represents the niche strategy deployed for a particular market situation. The unit of observation is the radically new high-tech product, meaning "radically new in the market and state-of the art in their respective disciplines" (Ortt 2012, p.1). The product is necessarily defined and distinguished based on three elements: the functionality it provides, the technological principle(s) on the basis of which it operates, and the main components of the system – alternatively termed first tier of sub-systems (Ortt & Suprapto 2011).

The product may be introduced by a single firm or by a group of firms. In any of these cases, the research will use the term 'company' to refer to the central actor(s) in the network; which exerts an important degree of coordination on the other firms in the network. For example, for the automotive industry this actor is typically represented by the vehicle manufacturer – e.g. Volkswagen, Audi, BMW, etc. – while the other firms in the network are represented by suppliers of the company, particularly first tier suppliers – e.g. transmission manufacturers.

4.3. SELECTION OF INDUSTRY: AUTOMOTIVE

The focus of the research is on the automotive industry. The decision is deliberate and was based on several arguments. First and foremost, an industry had to be selected in which sequences –of niche strategies ideally, but at least of niche markets– was likely to exist in the first place. The automotive industry bears such a characteristic, given that quite some innovations are first introduced in racing and later progressed to a consumer market. For example, "[h]eadlights, windshield wipers, disc brakes, diesel, and hybrids […] are all technologies that owe their current state of existence to the 24 Hours of Le Mans" (Jaynes 2014). Another typical sequence is the migration from luxury cars to regular cars via market skimming.

Secondly, the automotive industry is ultimately oriented towards a mass market. This aspect is essential given the managerial expectation from sequences of niche strategies, i.e. the progressive removal of the barriers hampering large-scale diffusion.

Thirdly, given that the automotive industry is geared towards a consumer market, the likelihood of available documentation on the selected cases is expected to be greater than in a business-to-business market.

Lastly, the selected industry should account for a long-enough market adaptation phase. During this span of time, there would likely be numerous niche applications, and primarily niche strategies – expected to be at least two, such that a potential sequence of niche strategies may be investigated. The automotive industry appears to elicit this characteristic as well. For instance, Naunheimer et al. (2011, p.41) report that "[v]ehicles and transmissions are developed cyclically and have a relatively long product and production lifecycle."

4.4. CASE STUDY PROTOCOL

As presented under section 4.1.5, the case study protocol should include the data collection procedures, the case study questions and a guide for the case study report. The guide typically contains an overview of the expected chapters from the individual case report. In addition to these elements, the current protocol will also present the visualisation tools. They will depict the legend, and will be used as templates.

4.4.1.DATA COLLECTION PROCEDURES

All cases are documented according to the template provided in Appendix 2: Template for Data Collection. The sources include journal articles, books (sections), patents; but also specialized magazine articles, web pages and electronic documents. The sources are expected to corroborate one another. Whenever there are conflicting sources, a resolution must be sought; with the inconsistent information explicitly highlighted and excluded from further analysis.

4.4.2.OUTLINE OF CASE STUDY REPORT

For each case study on a radically new high-tech product, the case report should detail upon the following aspects, as presented under the left-hand side column of Table VI. The right-hand column presents the rationale for the inquiry into the respective aspects.

Table VI: Sections of the case study report

Section	Comments
1. Introduction	
2. Chronology of strategic niches	Given that the focus of the research is on strategic niches, a clear description of their chronology is required as a basis for further analysis.
3. Chronology of niche strategies	This section represents the basis for the investigation of the influence of niche strategies on the core and contextual factors. The effect of external factors on the market context will also be investigated herewith.
4. Change in the barriers to large-scale diffusion	This particular section synthesises the findings regarding the change of the barriers to large-scale diffusion.
5. Sequence of niche strategies	With the chronology of the niche strategies depicted under point 3 , the focus lies on uncovering the potential logic and rationale for the emergence of sequences. Furthermore, under this section the reasons for opting between niche, large-scale introduction or a wait-and-see strategy will also be investigated.
6. Conclusion	The main objectives of the chapter are to answer the research questions based on the case evidence, and present any potential theoretical or managerial implications uncovered during the investigation.

4.4.3.CASE STUDY QUESTIONS

Each of the cases to be investigated is expected to reveal an answer for the set of questions presented under the left-hand column of Table VII; the questions are arranged correspondingly to the section from the case study report. The right-hand column presents the rationale behind or the role of the questions.

Table VII: Case study questions

Questions per section	Comments
Introduction	
A. Define the radically new high-tech product, i.e. the functionality it provides, the technological principle(s) on the basis of which it operates, and the main components of the system / first tier of sub-systems.	This aspect is important for construct validity. In absence of a clear definition, the investigation on the niche strategies, or the changes in the barriers hampering large-scale diffusion for that matter, might include aspects corresponding to other technologies.
B. Identify and describe the invention hallmark.	There may be important changes taking place between the time of the invention and the first market introduction. By having a clear view on the invention hallmark, the initial state of the barriers hampering large-scale diffusion around the first market introduction is expected to become clearer.
Chronology of strategic niches	
A. Identify and describe the first market introduction of the technology, and the hallmark of large-scale diffusion.	As defined in sub-section 2.3, strategic niches can only emerge between these respective hallmarks. Therefore, the question is steering in directing attention on the relevant time period to be investigated. Niches occurring outside this time interval fall outside the scope of the research.
B. Present chronologically the different niche applications of the technology.	By identifying the strategic niches it becomes easier to pin-point the different changes in the barriers to large-scale diffusion and to narrow in on the specific niche strategies employed.
C. Depict visually the different niche applications, starting with the first market introduction and concluding with the large-scale diffusion.	This is meant merely as visual support for the reader. The diffusion curves serve only as an indication of sales, and are by no means indicative of the actual diffusion rate.
Chronology of niche strategies	
A. **Describe chronologically the niche strategies and the respective market situations.**	The answer represents the descriptive support for the further interpretation of the case results. Figure 11 should be used as template.
B. **Depict visually the barriers to large-scale diffusion over the market adaptation phase, and the influence of the different factors on the core and contextual factors.**	By visualising the change in the barriers to large-scale diffusion, there are at least two benefits: firstly, for the reader it becomes easier to corroborate the text with the graphic interpretation; secondly, the supporting visuals are also helpful in answering some of the case questions from the next section.
Change in the barriers to large-scale diffusion	
A. Depict graphically the change in the core factors throughout the market adaptation phase.	The graphic representation will be based on a qualitative assessment of the barriers at specific moments in time. Figure 12 should be used as template.
B. How did the barriers to large-scale diffusion change over the span of the market adaptation phase?	The answer contributes towards addressing research question 2.
C. What was the influence – if any – of niche strategies on the barriers to large-scale diffusion?	The answer can support or question the hypothesised effect of niche strategies on the barriers to large-scale diffusion, as presented under Figure 7: Conceptual model.
D. Were there any external factors – i.e. apart from niche strategies – which had	Similarly to question C above, the answer relates back to Figure 7: Conceptual model.

an influence – i.e. remove / create – on the barriers to large-scale diffusion?	
E. Why did the barriers to large-scale diffusion change over the market adaptation phase?	The answer represents the input for addressing research question 3.
Sequence of niche strategies	
A. Depict visually the series of niche strategies.	This is meant as a supporting visual for the reader.
B. From a market perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.	The answer represents the input for addressing research question 6.
C. From a company (incl. network of companies) perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.	The answer represents the input for addressing research question 6.
D. Why did a sequence of niche strategies – if any – emerge during the market adaptation phase?	The answer represents the input for addressing research question 5.
E. Based on which criteria did companies opt for a wait-and-see, niche or large-scale introduction strategy?	The answer represents the input for addressing research question 4.
Conclusion	
A. How do the case results contribute towards answering the research questions?	The question is meant as a summary of the case results which contribute towards answering the research questions, and therefore towards meeting the research objective.
B. What are the theoretical implications of the case results?	The theoretical implications may reflect on the models and/or theories which for the basis for the case methodology; and revisions/additions. This question relates to section 10.1.
C. What are the managerial implications of the case results?	This question relates to section 10.2.

Please note that based on Table VII, the 6th research question is answered before the 5th. Although this might seem counter-intuitive for each particular case is arguably easier to look for patterns in the series of niche strategies –i.e. essentially look for sequences– and then infer into the underlying rationale. In contrast, once these results are aggregated, exploring patterns of typical sequences becomes very cumbersome due to the diverse nature of the cases from one another. In this later instance, typical sequences need be inquired upon based on a set of criteria; and therefore the regular order of research question no. 5 followed by 6 is resumed.

4.4.4. VISUALISATION GUIDELINES

Figure 11 represents the template for the visualisation of the market context, and the influence of the external factors and niche strategies on the core and contextual factors. Note that if one of the constructs from the figure –for e.g. core factor#2– is demarcated with a horizontal line, the meaning is that it has recently ended.

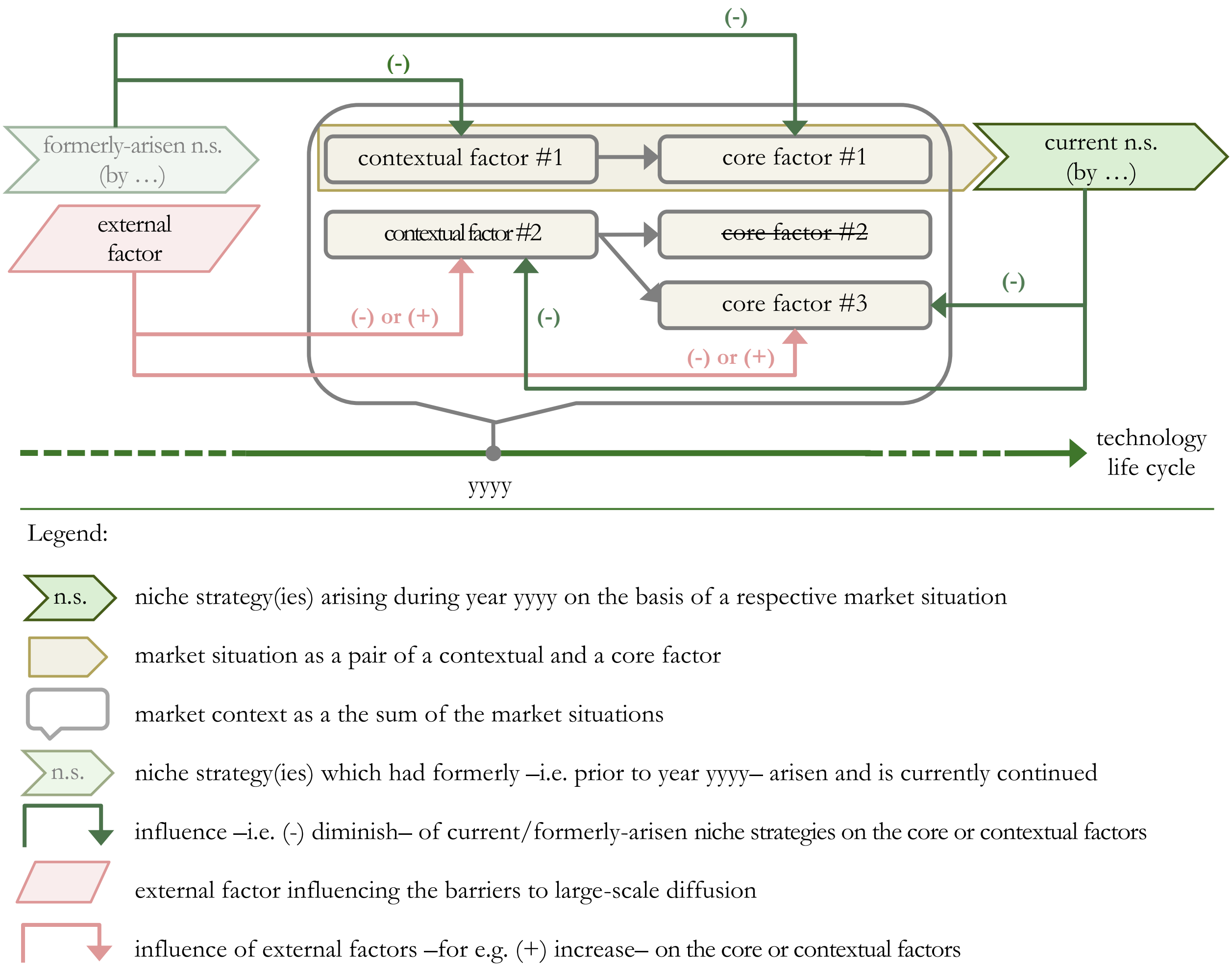


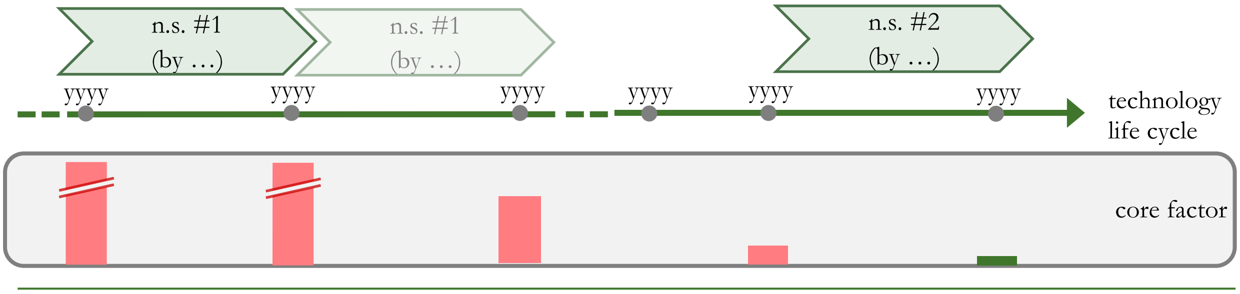
Figure 11: Template for the visualization of the market context, and influence of niche strategies and external factors on the core and contextual factors

Moving on to Figure 12, it represents the template for the visualization of the change in barriers, throughout the time period investigated for each specific case. Note that the legend under Figure 11 continues to apply for niche strategies.

The year just below the lower-left corner of a niche strategy represents the starting year; the year under the lower-right corner–the ending year. The dashed line on the technology life cycle axis represents a time period which has not been included in the investigation; as for e.g. due to lack of product introduction or case literature.

The observed magnitude of the barriers is represented by the height of the columns, under each corresponding year and factor. For some years there may not be available information to assess the magnitude, and in that case the symbol is eluded. This should not be read as if the barrier has seized to hamper large-scale diffusion. The sign for this latter aspect is represented by the small dark green column.

If the barriers are significantly larger than the allowed space, the inclined lines are used to show this aspect. They should be read as 'part of the column height excluded from the representation'.



Legend:
see Figure 11 and associated explanations for current figure

Figure 12: Template for the visualization of change in barriers

4.5. SELECTION CRITERIA FOR CASES

The set of cases should be sufficiently heterogeneous to allow for relevant insights to be drawn. The cases should differ in terms of the length of the market adaption phase for the respective technologies, and the number of central actors – i.e. single / multiple actors – involved in the development and application of the technology in niche markets.

The second criterion refers to how critical is the technology to the automobile (as a vehicle): critical/primary functionality (e.g. engine, transmission, braking system), or secondary functionality (ABS - given that you can also break without it). An exhaustive list of technologies would also include 'optional' features. For the current case, such technologies were eluded since they were not expected to contribute significantly towards the research objective.

The last criterion refers to how disruptive was the technology to the innovation system. Innovations that do not disrupt the system around automobiles –which can be considered to consist (for e.g.) refuelling infrastructure, highways, etc.– and innovations that do disrupt this. An example of the latter would be the electric car or the hydrogen/fuel cell car.

5. CASE REPORTS

5.1. CASE 1: DUAL-CLUTCH TRANSMISSION (DCT)

5.1.1.INTRODUCTION

The majority of automobiles in use today are powered by "internal combustion engines with cyclical combustion, working on the spark-ignition or diesel principle." (Naunheimer et al. 2011, p.49) A gearbox is essentially an output converter. The DCT, much like any other gearbox, must (1) enable the vehicle to move-off from rest, (2) adapt the power flow –i.e. convert output torque and output speed (to the drivetrain), enable reverse motion– (3) enable consistent power transmission and (4) control the power matching (adapted from Naunheimer et al. 2011, p.51).

The dual-clutch technology is a type of gearbox which was invented in 1935 – and patented in 1939 (see Kegresse 1939) – by Adolphe Kégresse, a former engineer of Citroën. The inventor is also known for inventing the half-track vehicle (Scoltock 2012). After Kégresse's departure from Citroën, he developed the AutoServe transmission, which he later successfully test fitted on a Citroën Traction Avant –a passenger car– in 1939 (Olivi 2013).

The core idea standing on the basis of the DCT concept was "to split a manual gearbox into two halves. One half of the transmission carries the odd gear ratios, while the other carries the even gear ratios" (Goetz et al. 2005, p.951). Each half is represented by an input shaft and a layshaft – the latter carrying the gears and synchronizers. The "two independent sub-gearboxes [are] each connected to the engine via its own clutch" (Naunheimer et al. 2011, p.172); one clutch for odd gears, and another for even gears (Senatore 2009).

"The main component, i.e. the dual clutch, is classified as either a wet-running or a dry-running system." (Naunheimer et al. 2011, p.174). Corresponding to the two clutches are two transmission shafts, placed either concentrically – i.e. nested in one another to save up space (see Naunheimer et al. 2011, p.174) – or in parallel – to decrease manufacturing costs (see Sutton 2007). Lastly, a transmission control unit is both responsible for the "AMT [i.e. automated manual transmission] control (activation of shifting elements such as synchronizers) and an AT [i.e. automatic transmission] control (clutches with powershift-algorithm)." (Naunheimer et al. 2011, p.587) The complete technological description falls beyond the scope of the current report. Interested readers are advised to turn to Naunheimer et al. (2011).

Most importantly, on the basis of its technological architecture DCT "shifts can be achieved without sensible torque gap [i.e. no discontinuity in torque transmission when disengaging the clutch], by applying the engine torque to one clutch just as the engine torque is being disconnected from the other clutch" (Senatore 2009, p.94). For the passengers, this entails "gentle, jerk-free changes with the same relaxed driving style found in automatic combined with the efficiency of a manual transmission. It is as smooth as the most sophisticated automatic transmission, but more economical than a conventional automatic; it is easy to drive as a standard auto, faster and more responsive than manual gearbox on high performance cars." (Senatore 2009, p.94)

Naunheimer et al. (2011, p.172) note that the "original intention [for the DCT] was to furnish heavy commercial vehicles with technology which provided for driving without power interruption." Whatever the intention, at the time of the invention the torque convertor for conventional automatic transmissions was more cost effective and Kégresse's system was not looked at again until the 1980s (Olivi 2013; based on Scoltock 2012), which will be discussed in the following section.

5.1.2. CHRONOLOGY OF STRATEGIC NICHES

As early as the 1970s, Porsche's engineers at Zuffenhausen "had been intermittently tinkering with the idea of a fast-shifting dual-clutch automated manual transmission […] in the form of the Porsche DoppelKupplung [PDK]" (Andropoulos 2015). The first market niche application was in the 1980s, via Porsche's endurance car programme and Audi's rally racing programme. Approximately two decades later, in 2004, the DCT was featured on consumer diesels which would diffuse into a mass market. By 2007, at least one million units had been produced, the vast majority of which by Volkswagen Group –in collaboration with transmission supplier BorgWarner– in the production facility located in Kassel, Germany.

Before describing the subsequent strategic niches, given that the application in racing is not a consumer market per-se, an explanation is in order as to why this can be regarded as the hallmark for the first market introduction. Firstly, the application was not a pilot project or for testing purposes only, which would be the case for technological niches. In fact, Porsche had actively worked on solving the problems arising with the technology (Stoklosa 2013). Secondly, the transmission was used in real championships and endurance races (see Andropoulos 2015; Richardson 2003), which meant that the engineers were also concerned with the reliability of the parts, much like in the case of a regular consumer car. Thirdly, as it will be explained later, two remaining DCTs used in racing would eventually be sold. On the basis of the three arguments, the introduction of the DCT technology in racing resembles to a strategic niche, rather than a technological niche – for the distinction between the two, the reader is advised to refer to section 2.3.

RACING

For Porsche the "main vessel of PDK development was the 956/962 endurance race car program of the 1980s" (Andropoulos 2015). In 1983, a five-speed PDK was first introduced on the 956 race car, and later the technology migrated to the Porsche 962 (Russ 2008). Despite there were numerous technological problems associated with the transmission (Stoklosa 2013), a 956 PDK-equipped race car won a German national championship race (Russ 2008), and in 1986 a Porsche 962 won the 360 km long international race at Monza, as part of the World Sports Prototype Championship (Olivi 2013; Stoklosa 2013).

Audi gained access to the PDK technology through its then R&D director –dr. Ferdinand Piëch– who had been "part of Porsche's controlling family and designer of the benchmark Porsche 917. So it came to pass that Audi Sport would work with Porsche on development of a PDK 'box for its rally quattros" (Richardson 2003). The first introduction by Audi of the dual-clutch technology was in November 1985 on the Audi Sport quattro S1 Evolution 2, as part of the Austrian non-WRC [World Rally Car] Semperit Rally (Richardson 2003; AudiWorld 2003). Audi's only World Rally Car event run with PDK was in the same year as part of the Lombard RAC Rally (Richardson 2003). Following Audi's withdrawal in 1987 from the Group B of the World Rally Championship, the only two experimental PDK gearboxes owned by the rally team were sold to Waiter Rohrl, the driver of the Audi Sport Quattro S1 Evolution 2: one mounted on a rally car, and the other as spare parts (Richardson 2003).

The PDK transmissions on the Audi rally cars were essentially the outcome of a technology transfer from Porsche, as explained in the earlier paragraph. Thus, the applications of the technology both by Porsche and Audi are considered to represent the same strategic niche: racing. It started in 1983 with the Porsche 956 race car and ended with Audi's withdrawal in 1987 from Group B of the World Rally Championship.

SPORT CARS

In 1988 "Porsche's dual-clutch PDK transmission […], as developed in the 962 program, was slated to appear in the 969 [model]" (Ludvigsen 2005, p.114), but was cancelled 18 months before its launch. The high-end sport car would have featured either a manual or a PDK transmission, depending on the driver's preference. The planned volume for 1990 –both manuals and PDK– was 2,500 units at a hefty price tag of $100,000. The idea for the car was scrubbed, and it was replaced by a model with a revised engine version (Ludvigsen 2005) and a ZF tiptronic gearbox – automatic transmission with torque converter (Stoklosa 2013). Despite having been readied for production, the transmission was never introduced in the market and will not be regarded as a niche application of the technology. The event is nevertheless relevant for the later investigation of the market situation around the time when the 969 model was under development by Porsche's engineers.

In fact, Volkswagen and Audi –the latter being owned by the Volkswagen Group as of 1964-1966– in collaboration with transmission manufacturer BorgWarner, were the first to introduce the dual-clutch technology in a consumer market; although initially restricted to compact sport cars. Audi introduced the DCT in the summer of 2013 under the name of S tronic on the Audi TT 3.2 quattro, and several months later Volkswagen under the name of Direct-Shift Gearbox (DSG) on the Golf Mk4 R32 (Stefanini 2003; BorgWarner 2014). Commenting on the year 2003, Volkswagen AG (2004, p.50) notes that "the sporty flair of the Golf, the Audi A3 and the Audi TT [was] enhanced by the combination of the new dual-clutch DSG® direct shift gearbox with the powerful 3.2 l VR6 engine."

The gearboxes were produced at Volkswagen's factory in Kassel, Germany, which was capable of manufacturing 1,000 units per day (Stefanini 2003). The technology had not been restricted to compact sports cars alone and in approximately one year it expanded to conventional diesel cars as well, "enhancing their performance and delivering even lower fuel consumption" (Volkswagen AG 2004, p.50). By the end of 2004, in Europe alone, the DualTronic –the name given by BorgWarner to the DCT– technology was made available on five additional models of the Volkswagen Group (BorgWarner 2014), "on the Touran, Golf, […] Skoda Octavia, SEAT Altea and SEAT Toledo" (Volkswagen AG 2005a, p.23).

The application in sports cars or consumer diesels of the DCT technology can be considered to be the same product application, with DQ250 being the code name of the transmission. Although the product application is the same, the market for sport cars was essentially a niche market, whereas the one for consumer diesels was geared towards a mass market. In other words, the niche application for sport cars had quickly scaled up to include a mass market for regular diesel cars: by April 2005 more than 150,000 DSG units had been manufactured (Volkswagen AG 2005b); and one year later –in August 2006– the "the Kassel plant announced the production of the 500,000th direct shift gearbox" (Volkswagen AG 2007, p.93). The year of 2004 will be regarded as the hallmark for mass market introduction, given that the market had quickly scaled up after the introduction in consumer diesels.

SUMMARY

The niche applications of the DCT technology were as follows: racing cars by Porsche and Audi, followed by sport cars of Volkswagen and Audi. Figure 13 presents this schematically.

In 2005, the DCT was introduced on the 1001 horsepower, 400 km/h supercar: the Bugatti Veyron. The car was a project of Volkswagen; with the transmission developed by Ricardo, a British engineering firm, in cooperation with the engineering team of Bugatti and Volkswagen. The DCT on the Bugatti Veyron was initially planned to be manufactured in very low volumes: only 300 had been planned. On the basis of the cooperation, Ricardo "could incorporate their [Volkwagen's] knowledge of specific lessons learned from their own DCT programme in the VW Golf" (Lewin 2006, p.14). Given that the technology had already been applied to consumer diesels and was steadily diffusing towards a mass market, on the basis of the theory presented in sub-section 2.2, the application of DCT in supercars is regarded as a mature niche.

In 2007, the one millionth DualTronic module was produced in Germany (BorgWarner 2014). Except for Ricardo –supplying the transmission for the Bugatti Veyron supercar– the other companies (e.g. Getrag, Porsche) entered from 2007 onwards. This means that the great majority of the sales of DCTs up to 2007 were derived only from BorgWarner's production; with the exception being Ricardo's low volume production.

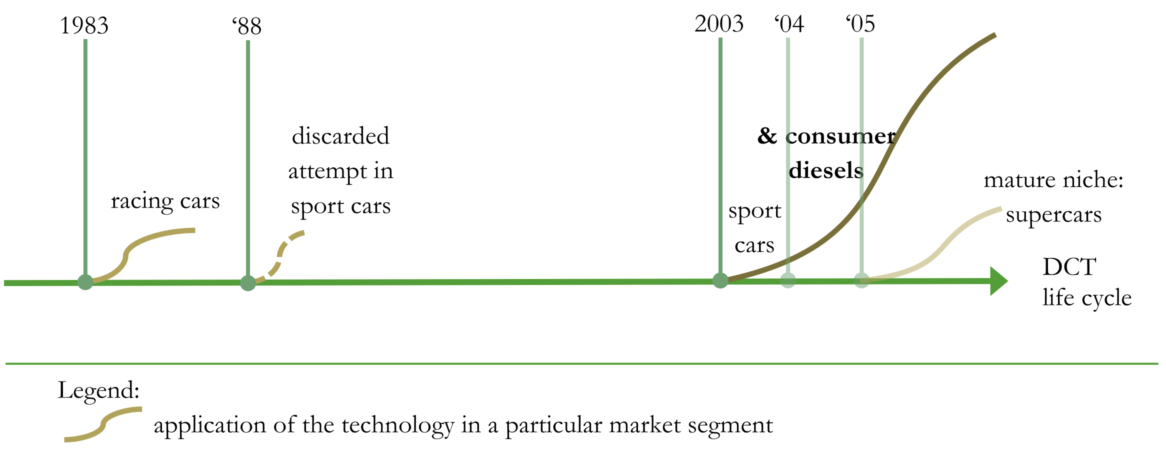


Figure 13: Graphic depiction of applications of the DCT technology in particular market segments

Another mature niche is the application of the DCT technology in commercial vehicles –more specifically in light trucks– by Fuso, a subsidiary of Daimler Group, under the name of "Duonic" in 2010. Also, Volvo Trucks was the first manufacturer in the world – in 2014 – to adapt the technology for use in heavy trucks, under the name of I-Shift Dual Clutch Gearbox.

In August 2009, Porsche and Volkswagen AG announced the "comprehensive agreement to create an integrated automotive group with Porsche led by Volkswagen […] Under this agreement, Volkswagen will initially take a 42.0 percent stake in Porsche AG by the end of 2009, and it will also see the family shareholders selling the automobile trading business of Porsche Holding Salzburg to Volkswagen. The plans will culminate in the merger of Porsche SE with Volkswagen. This is expected to be completed in the course of 2011" (Volkswagen AG 2009).

For the visual representation of the complete pattern of development and diffusion, interested readers are directed to Appendix 3: Patterns of development and diffusion.

5.1.3.CHRONOLOGY OF NICHE STRATEGIES

Before presenting the barriers which were found to hamper large-scale diffusion in the case of the DCT technology, it is worthwhile to comment on those barriers which were not active. Firstly, the core factor relating to complementary products and services was not encountered. On one hand, the complementary products –such as transmission oil– were largely similar to other transmissions which had already diffused in the market, therefore it wouldn't have posed a problem. On the other hand, complementary services –such as maintenance or technical service over the transmission's life time– would be fairly different with respect to other transmissions in production. Nevertheless, since the DCT diffused on series production vehicles, rather than in the aftermarket, it meant that large vehicle manufacturers –for instance Volkswagen– could readily adapt their existing service and maintenance to accommodate the new technology as well. An added advantage for mechanics would have been the resemblance to a manual transmission, as stated in the introduction to this case.

Secondly, the core factor related to suppliers was also not encountered. Section 5.1.3 details further on this topic, under the sub-section entitled "2001-2002".

1983-1987

The DCT technology was first introduced in racing in the 1980s, when "computers to control the gear shifts [had become] compact enough" (Senatore 2009, p.95). However, the lacking knowledge of the technology – electronics, control systems, friction materials– affected the availability of the product with sufficient quality, and the availability of a production system, as shown in Figure 14.

The transmission was "very bulky and complicated, with many reliability issues stemming from both the electronic and hydraulic systems" (Andropoulos 2015). It was so riddled with problems that the "PDK was only reliable in the sense that it would reliably explode every so often, chucking shafts, gears, actuators, and the like all over the racetrack. It's said that each time Porsche tracked down a problem and fixed it, something new went wrong" (Stoklosa 2013). As Naunheimer (2011, p.172) notes "[t]hese transmissions were not suited to serial production because the control quality of the systems was not yet sufficient." Summing up, during this period the poor reliability of the new high-tech product remained largely at the same level as before.

Furthermore, only a few PDK transmissions would have been necessary for racing applications. Although the cases did not reveal how many were used by Porsche, "Audi Sport had only two PDK 'boxes, for selected events" (Richardson 2003). This implies that there was no readily available production system, with the most likely cause for this being the lacking knowledge of the technology – the electronics, control systems and friction materials.

However, despite all of quality-related problems and "its [the transmission's] considerable weight penalty of 88 pounds (which is significant in a sub-2,000-pound race car)" (Andropoulos 2015), Porsche and Audi were eager to experiment with the technology given the promise of faster lap times, on the basis of both quicker gear shifts (Andropoulos 2015) and uninterrupted power delivery to the drivetrain (Richardson 2003). The reader is advised to note that in Figure 14 and all remaining figures of the case, Audi is listed as VAG since by the 1980s it had already been acquired by Volkswagen Group.

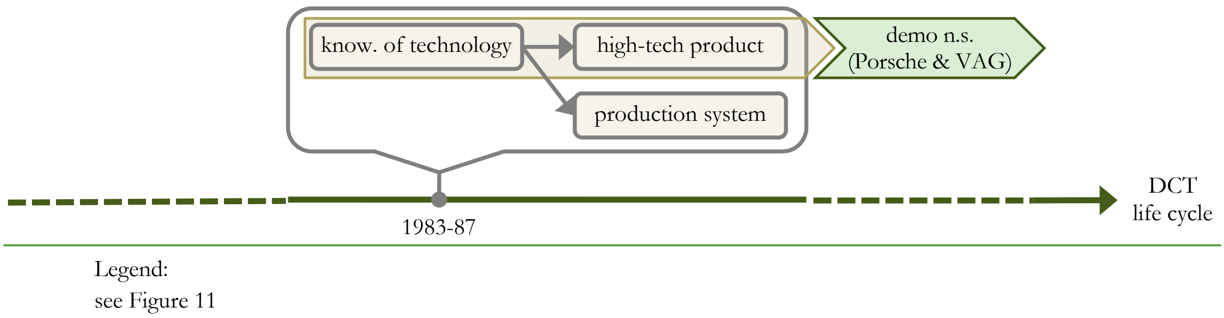


Figure 14: Market context of the DCT technology between 1983-1987

One may argue that the DCT was introduced via a top niche strategy, whereby "products can be made to order, in small numbers, for a specific top-end niche of the market" (Ortt et al. 2013, p.7) willing to pay a premium for the technology. Although there were only a handful of DCTs probably produced for racing, they were ultimately not sold by Porsche to Audi, or even to their own Porsche racing team. Furthermore, even if the two PDKs owned by Audi's rally team were sold to driver Waiter Rohrl, they were not made to order for this buyer. In this light, the DCT was not introduced via a top niche strategy.

Rather, in this context Porsche and Audi applied the 'demo, experiment and develop' niche strategy, with the market situation being the lacking knowledge of the technology affecting the availability of the product with sufficient quality. "As part of the strategy experimenting with the product is important to develop the product further" (Ortt et al. 2013, p.6), which –as mentioned earlier– Porsche regularly did. Furthermore, only selected sources reported the inherent problems with the technology in the realm of racing, whereas many focused on the great benefits the DCT had shown in racing. This hints that indeed the goal of demonstrating the product in public was achieved. Direct revenue from implementing the niche strategy would have been derived from sponsorship fees or rally prizes.

The demonstration of the technology could be considered too successful if looked upon from another perspective. Given the uninterrupted power delivery of the DCT, in the 1980s the FIA –the governing body over world motor sport and the federation of the world's leading motoring organizations– banned its application in racing, as shown in Figure 15 by the influence of the niche strategy on 'institutional aspects'; whilst the effect on 'accidents / events' represents all the situations when the superior technology potential of the DCT technology –for e.g. the Lombard RAC Rally (see Richardson 2003)– was demonstrated.

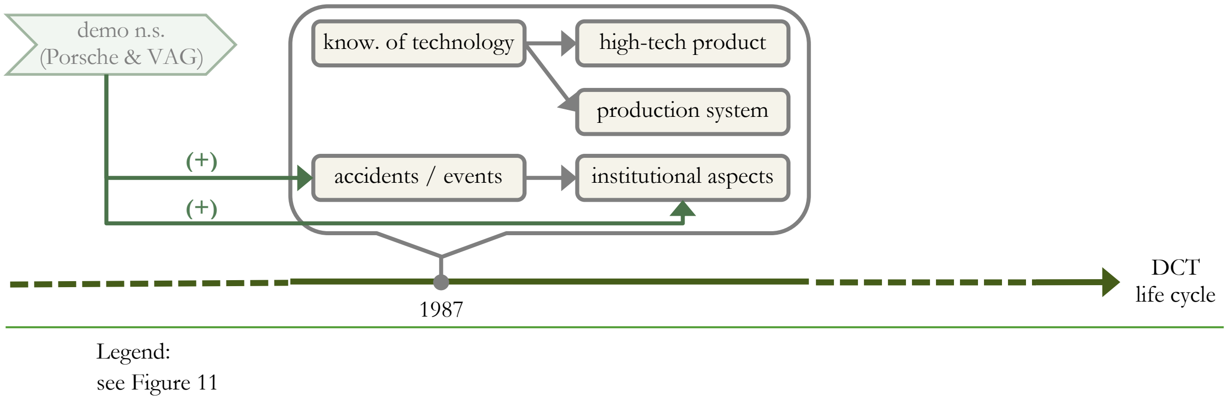


Figure 15: Market context of the DCT technology around the year 1987

1988-1989

Without the possibility to experiment in racing, Porsche had attempted in the late 1980s to introduce the PDK with their 969 model. This implies that with the shift to a consumer market, the institutional aspect presented in the earlier section would no longer hamper diffusion.

The tooling to manufacture was developed for the production of 16 prototypes of the 969 sport car (Ludvigsen 2005). This would indicate that there were some available production systems for the manufacturing of the complete car; at least for the production of 2,500 units as initially predicted. However, this relatively low number cannot be regarded as industrial production. Put differently, with this production rate it would require 40 years to produce one million units. This implies that there was still no readily available production system.

Porsche "installed versions of the PDK in several prototype road cars, but the engineers did not consider it ready for primetime given the limited electronics technology of the day and its lack of refinement for road use" (Andropoulos 2015). Thus, the lacking knowledge of the technology was also the cause for the deficient quality of the radically new high-tech product. Qualitatively speaking, it would seem that although the technology was worked upon during the 1980s, by and large the reliability of the new high-tech product was deficient.

Also, the model in which Porsche decided to introduce the PDK was very expensive, at over $100,000, and a low number of models were planned for production. Thus, if Porsche had continued with the introduction, the technology would have been introduced via –at least– a top niche strategy. Figure 16 illustrates this.

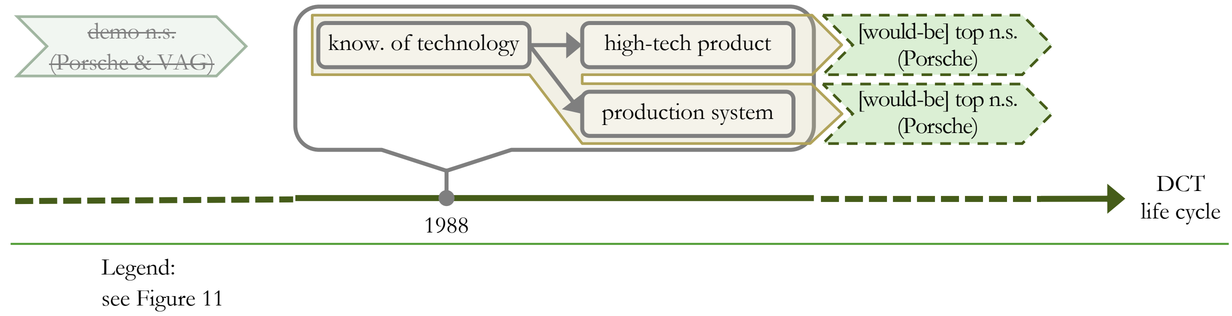


Figure 16: Market context of the DCT technology around the year 1988

However, another external factor affected the willingness-to-pay of Porsche's main market: the US experienced an economic recession in the late 1980s following the stock-market crash of 1987 and a "precipitous decline of the US dollar. […R]egrettably [Porsche's] customers, 'the doctors, dentists, lawyers, and NASA engineers' in the US were also heavily invested in the stock market" (Ludvigsen 2005, p.112). This external factor would have arguably counteracted the attempted top niche strategy, given the decline in spending power of the target market segment.

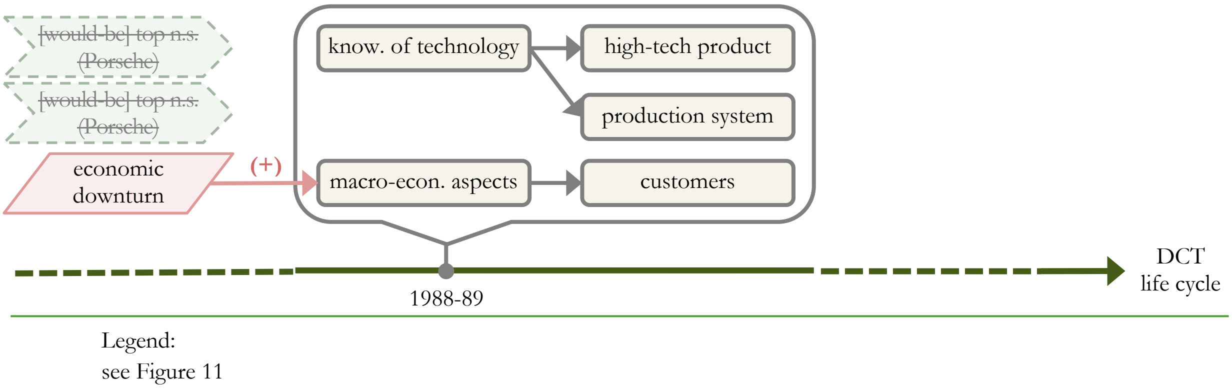


Figure 17: Market context of the DCT technology between 1988-1989

Following the decision to terminate Porsche's 969 project, the special tools prepared for the manufacturing of the vehicle were scrapped; also destroyed were 15 out of the 16 prototypes (Ludvigsen 2005), with the sole remaining prototype not seen since.

2001-2002

In 2001, transmission manufacturer BorgWarner announced its proprietary DualTronic technology had been "selected for 2003 production by a major European automaker" (BorgWarner 2014). The vehicle manufacturer would turn out to be the Volkswagen Group, as presented in an earlier section.

Available information on the next market context corresponds to the niche application of the technology in sport cars: the Audi TT 3.2 quattro, the Volkswagen Golf Mk4 R32, and on a sporty version of the Audi A3.

Several developments had removed former barriers to large scale diffusion prior to this strategic niche in sport cars. For instance, BorgWarner's Transmission Systems president and general manager Robert D. Welding estimated the price of the DCT to be lower than the competitive alternatives: conventional automatic or continuously variable transmission. Also, reliability in a consumer market would no longer pose an issue, given BorgWarner's advancements in friction materials and high-tech lubricants for wet clutches, and its capability in electronic controls (Visnic 2000). Furthermore, the cumbersome control unit also became readily available, following its production by Continental in 2003 (Beecham 2005). Insufficient knowledge of mechanical and electronic controls no longer posed a problem for the product's reliability, quality and even price.

Volkswagen had also invested €150 million – or $172 million – in production facilities at Kassel, with a capable production rate of 1,000 units per day (Volkswagen AG 2002; Stefanini 2003).

Put simply, it means that just before the niche application in sport cars by Volkswagen and Audi, several core factors hampering large-scale diffusion had evaporated; more specifically the production system had become readily available, and the new high-tech product had a good price/quality compared to competitive products.

Interestingly, there was also a coordinated network of suppliers: Continental manufacturing the control unit, BorgWarner supplying the knowledge to produce the technology. This shows that although the absence of the suppliers core factor had not been hampering large-scale diffusion, as was argued in the beginning of the section, a well-coordinated network of suppliers can facilitate the diffusion; whereas as a non-existing one is nor hampering, but also nor facilitating it.

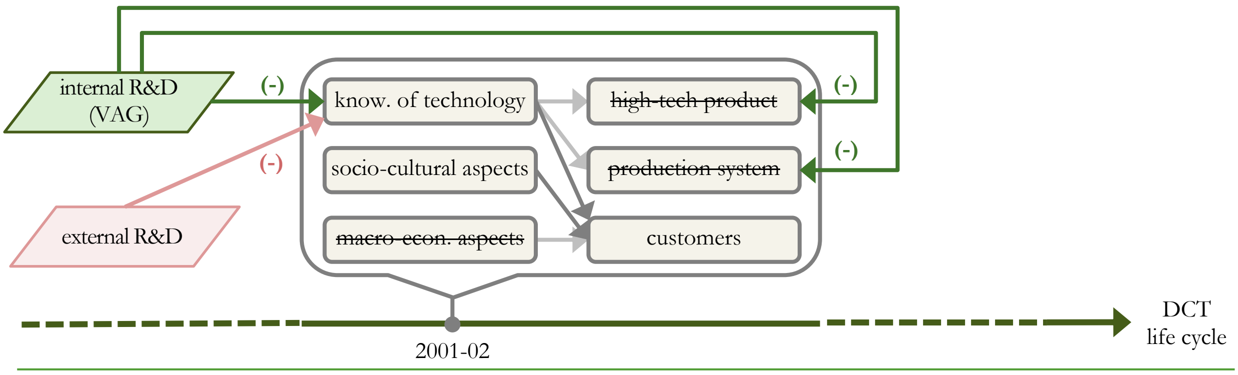


Figure 18: Market context of the DCT technology between the years 2001-2002

The factor 'external R&D' refers primarily to the development of mechanical and electronic control outside the particular application in DCT technology.

The factor 'internal R&D' on the other hand refers to a slightly different aspect. Volkswagen together with its coordinated network of suppliers –VAG from Figure 18– had worked on developing the DCT technology to ready it for the introduction in series production vehicles, i.e. to advance the lacking knowledge of the technology and improve the product's reliability and/or costs. However, in spite of the same actors being involved in the product introduction and the product development work beforehand, it cannot be argued that the niche strategy itself impacted the barriers. Rather, the 'internal R&D' altered the market context in such a way that the strategies made sense to begin with.

Furthermore, looking from the perspective of the two generic types of R&D illustrated in Figure 21, it also becomes apparent why 'external R&D' had no influence on the 'new high-tech product'. Any development in electronics or mechanics would have had to be applied by the company network on the specific DCT technology.

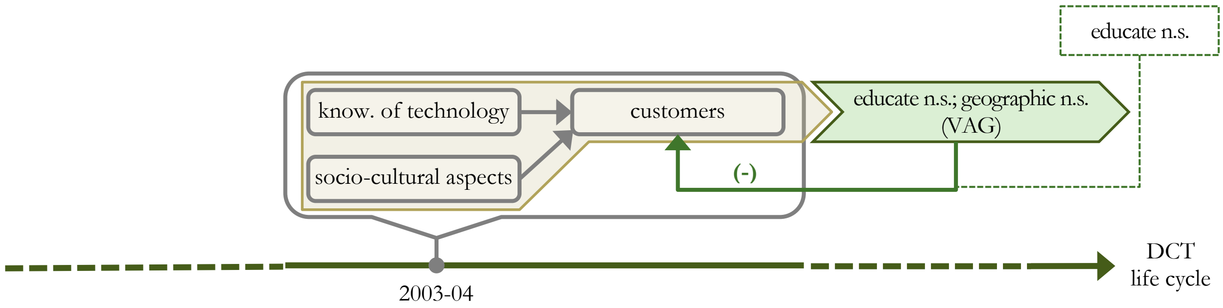
2003-2004

For the niche application in sport cars, Volkswagen Group –i.e. including Audi– used two niche strategies in parallel: educate and experiment, and geographic niche strategy.

The DCT was an automatic transmission in the end, and automatics had a history of being regarded as sluggish and slow. To reach the mass market Volkswagen still needed to educate the customers with respect to the technology's benefits: fuel efficiency, fast and seamless gear shifts. Following the 'educate and experiment' niche strategy in sport cars, Volkswagen could show consumers that the new transmission was anything but slow or sluggish.

In all fairness, the typical consumer's awareness of the product benefits would have been fairly limited even before 1988. However, in absence of explicit evidence and without a realized attempt at the product introduction, we simply couldn't conclude that it was already a barrier to large-scale diffusion. For instance, let us presume that in the late 1980s Porsche had targeted their very limited production of the 969 model only at selected Porsche owners with a good grasp of the company's technology developments in racing. The hypothetical scenario presents one instance where our earlier conclusion would have been proven wrong. Therefore, only beginning with the early 2000s will it be considered as a barrier to large-scale diffusion.

Volkswagen opted to target the technology in Europe, a market characterised at that time by an entrenched socio-cultural preference for manual transmissions on the basis of their greater fuel economy; but also by an emerging preference for automatic transmission due to the increasingly congested roads and cities (see Visnic 2000). The DCT transmission was perfectly positioned to offer the best of both worlds to European drivers.



Legend:
see Figure 11

Figure 19: Market context of the DCT technology between the years 2003-2004

Although the internal R&D most likely continued, it was not featured in Figure 19 because the factor 'knowledge of the technology' refers to the knowledge of customers, rather than that of the manufacturer.

As Volkswagen predicted in their Annual Report from 2003, "[i]n future the DSG will also be fitted in diesel-engined vehicles, enhancing their performance and delivering even lower fuel consumption." (Volkswagen AG 2004, p.50). The benefits of the technology were becoming apparent to the mass market; and so yet another barrier hampering large-scale diffusion had disappeared: "[e]ven customers of more comfort-oriented vehicles such as the Touran and Passat estate are interested, with every fifth Volkswagen customer choosing the direct shift gearbox" (Volkswagen AG 2005c). Volkswagen subsequently expanded into the U.S., and other geographies outside of Europe.

SUMMARY

Figure 20 presents the series of market contexts and niche strategies during the market adaptation phase; the formerly explained effects of niche strategies or external factors on the core and contextual factors are also featured.

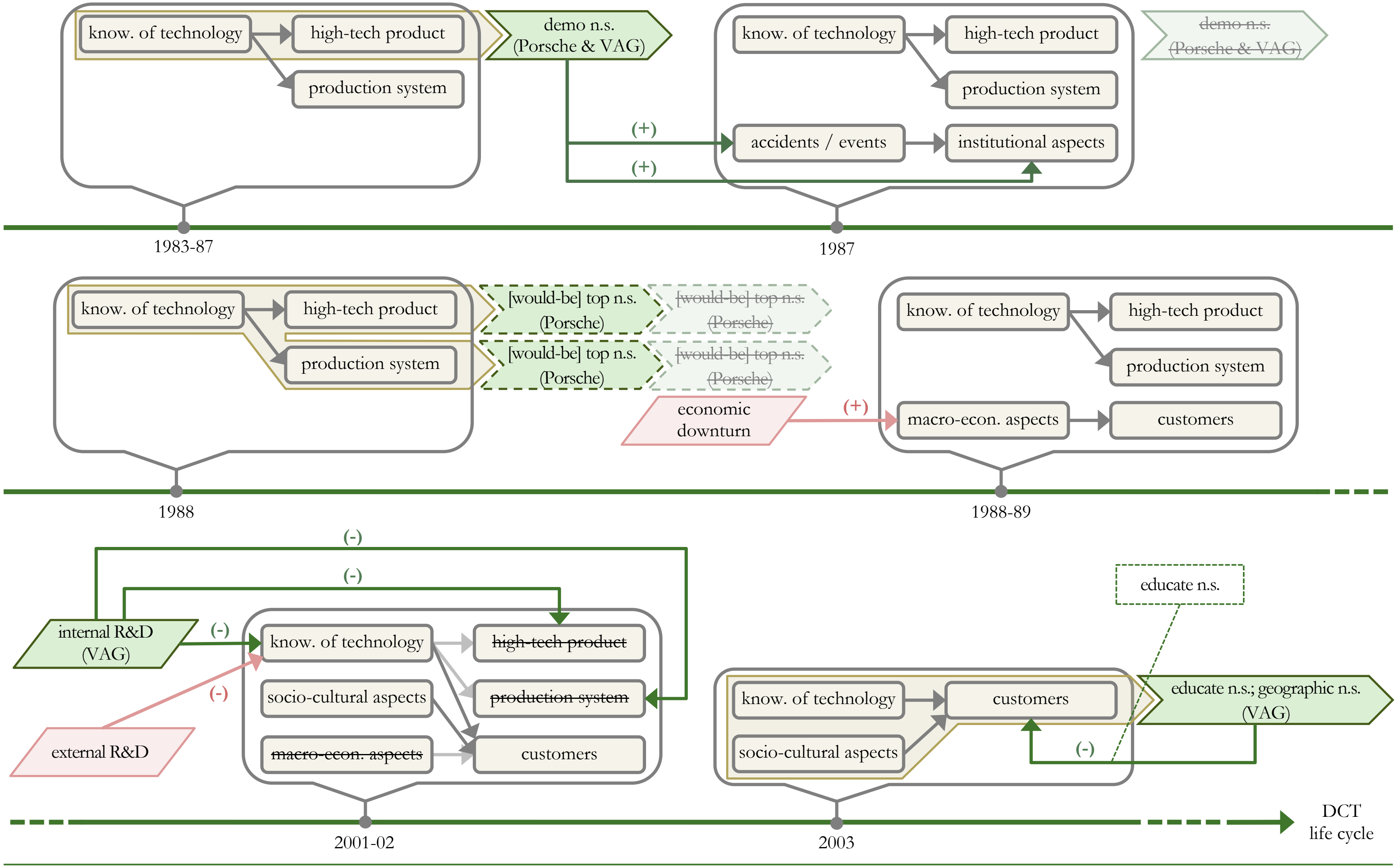


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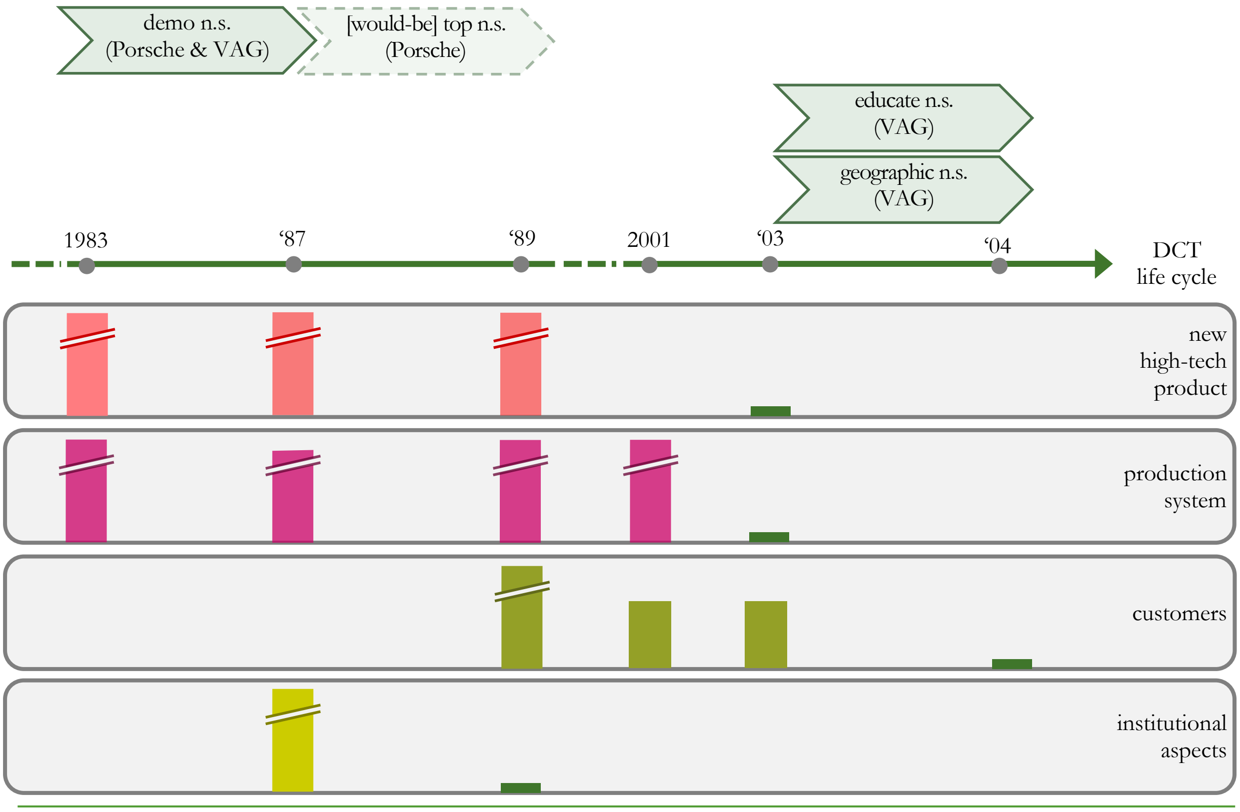
Figure 20: Chronology of market contexts, niche strategies and external factors – DCT technology

5.1.4.CHANGE IN THE BARRIERS TO LARGE-SCALE DIFFUSION

4.A Depict graphically the change in the core factors throughout the market adaptation phase

Figure 21 visually depicts the change in the core factors hampering large-scale diffusion for the case of the DCT technology. The detailed explanation of the qualitative –and at times quantitative, as in the case of the production system– evaluations can be found in section 5.1.3. The paragraphs just below Figure 21 are intended at succinctly summarizing the information and verbalising the visual representation.



Legend:
See Figure 12

Figure 21: Dynamics of the core factors hampering large-scale diffusion – DCT technology

Firstly, the 'new high-tech product' core factor had hampered diffusion from the perspective of cost and reliability. During the 1980s, both in racing and in the cancelled product introduction, these aspects did not show any major improvements: "each time Porsche tracked down a problem and fixed it, something new went wrong" (Stoklosa 2013). Hence, up until the late 1980s, this factor is represented to have remained at a fairly elevated level, i.e. it would have significantly hampered the diffusion. The lack of –documented– experimental projects or product introduction between 1989 and early 2000, meant that the status of the barriers was implicitly assumed as 'not changed'.

Secondly, there were two milestones in the production system. The first took place around 1987 when Porsche had 16 prototypes build –presumably some equipped with the DCT technology– and there was also available tooling to manufacture the 969 model. This aspect is represented by the slight decrease in the production system barrier in 1987 as opposed to the earlier period. However, after the 969 project was cancelled, the aforementioned tooling was destroyed, and therefore the production system barrier increased to the earlier level from 1983 when only a handful of purpose-built units could be made. Sometime around 2002, the factory at Kassel was constructed, which meant that industrial production became possible.

Thirdly, the customers' barrier first came into prominence following the stock-market crash of 1987. Porsche's target customer segment was impacted by reducing the willingness-to-pay for the adoption of the pricey 969 model, including its revolutionary technology. In 2001, the price pressures were reduced, but the lacking knowledge of the product's benefits hindered diffusion. This barrier is featured at a lower level than before given Volkswagen was still able to sell quite a significant number of units, despite the barrier. Porsche on the other hand, had given up altogether at introducing the product in the earlier instance.

Fourthly, institutional aspects completely blocked further introduction in racing in 1987. With the shift to the consumer market, beginning with Porsche's cancelled introduction, the barrier was no longer hampering diffusion.

Lastly, some barriers were not observed at all during the market adaptation phase of the DCT technology. These were: 'complementary products and services' and 'suppliers'.

4.B How did the barriers to large-scale diffusion change over the span of the market adaptation phase?

Firstly, one may notice that technological barriers –new high-tech product, production system– were more prevalent in market contexts towards the start of the market adaptation phase, whereas social barriers –customers, institutional aspects– tended to appear during and later in the technology life cycle. Partly, at least for the institutional barriers, the above insight can be explained by referring to the literature on responsible innovation. Midstream Modulation, for instance, fosters the belief that many socio-ethical issues spurring from technologies become acknowledged too late in the development cycle (see Fisher & Schuurbiers 2013).

Secondly, it is equally interesting to observe how technical barriers tended to dominate for approximately the entire length of the market adaptation phase, whereas social barriers were more erratic.

Thirdly, the type of market in which a company is active –for example a consumer market versus racing– can influence the strategic analysis of the market context, i.e. the manner in which the barriers are interpreted. In the case of the racing ban by the FIA, simply by changing the product focus to a consumer market the barrier was no longer hampering large-scale diffusion.

4.C What was the influence – if any – of niche strategies on the barriers to large-scale diffusion?

When looking at the influence of niche strategies on the barriers to large-scale diffusion, several aspects can be observed. Firstly, the mere demonstration of the DCT in the domain of racing rapidly seems to have led to FIA's ban on the technology. The uninterrupted power delivery offered a substantial time advantage. For example, when "[w]hen, in early November 1985, [Audi rally racing driver] Rohrl debuted the PDK E2 in the Austrian non-WRC Semperit Rally […] he blitzed the event. Fastest on all 24 stages, he won by 19 minutes. Devastatingly effective, this Audi Sport quattro S1 Evolution 2 [was]" (Richardson 2003). The institutional hurdle did not hamper large-scale diffusion in the consumer market, where FIA rules are not applicable. Summing up, the incident cares to show how the mere demonstration of a technology can lead to regulatory response.

Secondly, the 'educate and experiment' niche strategy helped to remove the lack of customer knowledge with respect to the benefits of the technology, particularly the shift response and product performance. This can be explained by the rapid rapidly up scaling of the technology from sport cars to consumer diesels. "Dual-clutch works particularly well when mated to diesel engines. Because diesels have a narrow rpm band, there are frequent interruptions in the torque flow. A dual-clutch transmission can be shifted without any break in torque flow" (Wernle 2005). By using their DSG technology in diesel cars, Volkswagen "has managed to further reduce CO2 emissions. At the same time, we [i.e. Volkswagen Group] have become the first manufacturer to meet the Euro 4 emissions standard with diesel vehicles featuring automatic gearboxes [i.e. DSG]" (Volkswagen AG 2005a, p.23).

In the span of approximately two years –from 2003 to 2005– "11 percent of Golfs [consumer diesels and sport cars] in western Europe c[a]me equipped with a dual-clutch transmission" (Wernle 2005). By 2006, "[t]he direct shift gearbox (DSG) ha[d] successfully established itself in the market. In 2006, we [i.e. Volkswagen Group] delivered almost twice as many vehicles with this innovative technology as in the previous year [i.e. than in 2005]. As a result, we will be able to make this technology available for other vehicle classes and enhance it systematically." (Volkswagen AG 2007, p.112). All in all, the evidence shows that the rapid subsequent adoption in the customer segment of consumer diesels can be explained by the success of the 'educate and experiment' niche strategy in convincing prospective customers that DCT does indeed offer the best of two worlds: fuel efficiency and the convenience of an automatic.

4.D Were there any external factors – i.e. apart from niche strategies – which had an influence – i.e. remove / create – on the barriers to large-scale diffusion?

Apart from the influence of niche strategies, there were also external factors –as defined under section 3.2– which played a role in the change of the barriers hampering large-scale diffusion.

One such factor was external R&D. Firstly, the computers had to become compact enough in terms of size in order to be fitted in cars. Secondly, the quality of the electronic controls increased, whereas the price decreased (Beecham 2005). These advancements were arguably driven by the general progression of electronics.

These developments spilled-over to the automotive industry and by deliberate efforts to apply the knowledge advancements –i.e. internal R&D by Volkswagen and BorgWarner– in the control module of the DCT, the core factors 'production system' and 'new high-tech product' were removed.

Another external factor that had an influence of the barriers was the economic downturn in the late 1980s. This induced a decrease in spending power of the customer segment targeted at the time by Porsche.

4.E Why did the barriers to large-scale diffusion change over the market adaptation phase?

In conclusion, the change in the barriers to large-scale diffusion over the span of the market adaption phase can be explained by three main aspects. Firstly, external factors –such as an economic downturn, autonomous improvements in other industries or even internal R&D by the central actor network– played a role. Note that the prospects of an emerging mass market influence the external factors, in the sense that it can direct the research and development efforts of actors, ultimately removing technological barriers; as was the case in the technological development of BorgWarner (transmission parts and knowledge), Continental (control unit) and Volkswagen (production facilities). Secondly, niche strategies introduced or removed certain barriers to large-scale diffusion. Thirdly, the change from one market to another –for e.g. from racing to a consumer market– influences the manner in which barriers are interpreted, and thus the market context.

5.1.5.SEQUENCE OF NICHE STRATEGIES

5.A Depict visually the series of niche strategies.

The subsequent niche strategies were: 'demo, experiment & develop'; followed by 'geographic' and 'educate' niche strategies. The central actor is represented by the vehicle manufacturer, for e.g. Volkswagen Group or Porsche. The subsequent niches correspond to the subsequent niche applications: first racing and thereafter in sport cars.

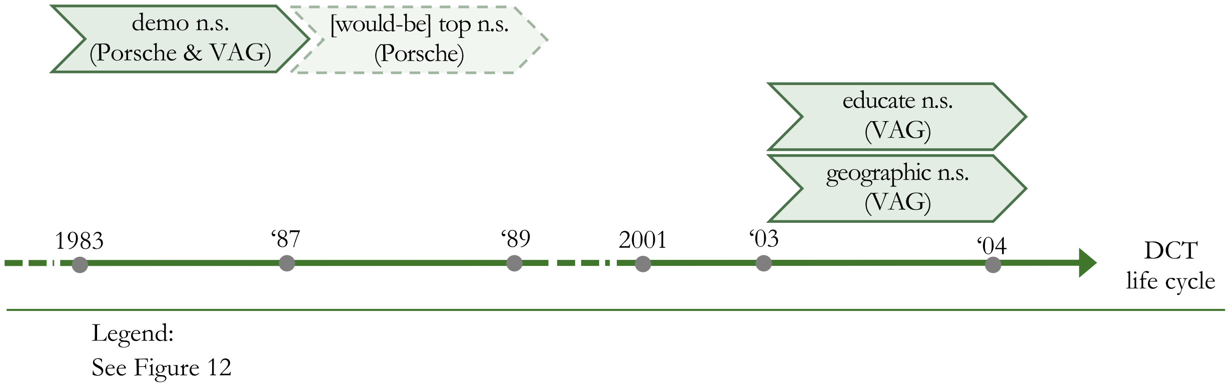


Figure 22: Chronology of niche strategies - DCT technology

The DCT technology life cycle presents a typical sequence in automotive which was described in section 4.3: the progression from automotive racing to consumer vehicles. However, please note that this represents a sequence of niches, and not of niche strategies.

5.B From a market perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.

Sequences of niche strategies were only observed as those deployed by the same central actor, i.e. VAG in this case. Thus, the discussion will ensue under the next case question 5.C.

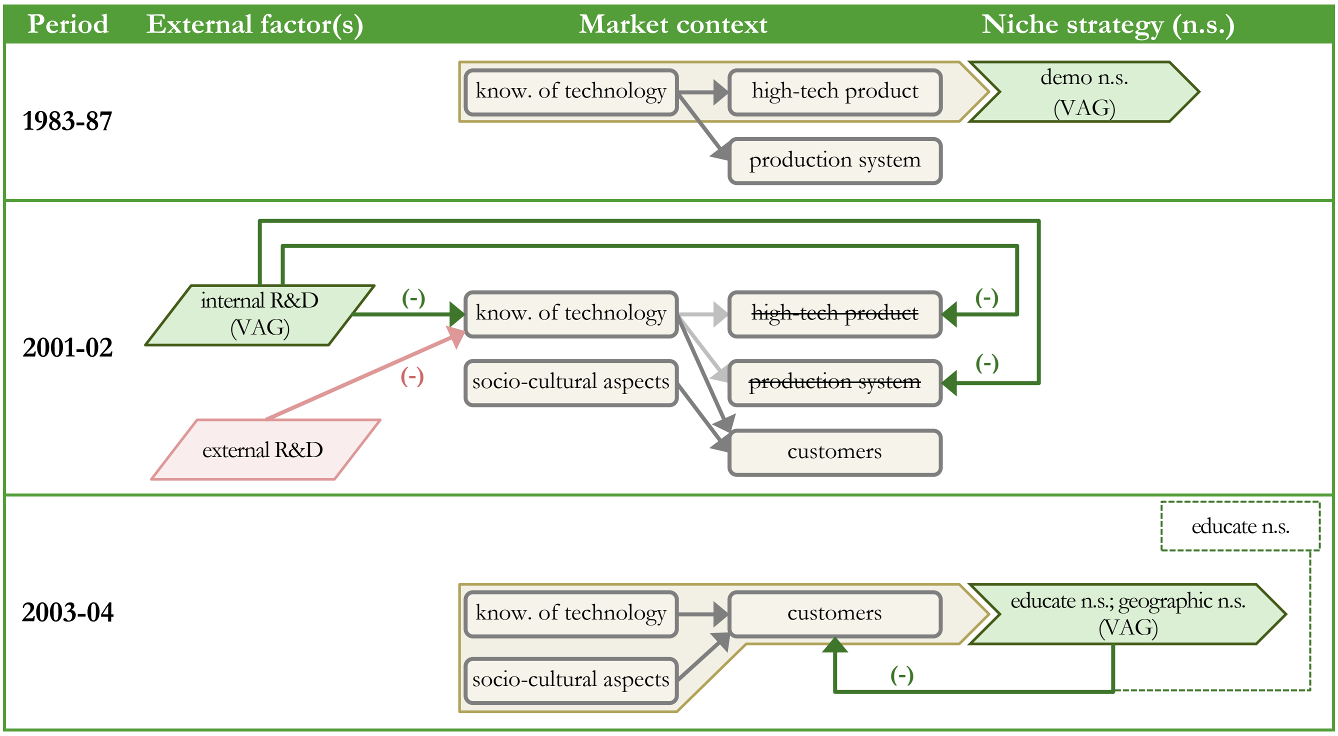
An observation corresponding to the market level perspective is that the niche strategies deployed –or about to be deployed– by the central actors during the early periods focussed on technological barriers, whereas those employed later aimed at social ones. This can be seen as a reflection of the dynamics of the barriers to large-scale diffusion during the market adaptation phase of the DCT technology.

5.C From a company (incl. network of companies) perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.

Using the classification from section 3.3.1, it should be decided under which category falls the time series of niche strategies presented in Figure 22. At a first glance, it would appear that the niche strategies merely follow one another, without a connecting logic. In support of that, more than 10 years passed –between late 1980s and early 2000s– without neither Porsche, Audi or Volkswagen showing interest in working on the transmission concept. In the remainder of the paragraph, it shall be proven that the critical tie is represented by a common decision maker: Ferdinand Piëch. Back in the 1980s, Audi –which was already part of Volkswagen Group as mentioned earlier in the case– "had a direct line to this [i.e. DCT] technology through its then R&D director Dr Ferdinand Piëch, part of Porsche's controlling family and designer of the benchmark Porsche 917. So it came to pass that Audi Sport would work with Porsche on development of a PDK box for its rally quattros" (Richardson 2003) (see Kacher 2010). But in 2001, when BorgWarner and Volkswagen presumably signed off on the production of the new transmission by 2003 (BorgWarner 2014), the same Piëch was chairman of the Volkswagen Group (see Kiley 2015) and would have had an important say in such strategic aspects. Therefore, we may conclude that the series of niche strategies is in fact a sequence.

There are two arguments that support the conclusion that the sequence was an emergent one. Firstly, there was no explicit evidence of VAG using the earlier application in racing as a stepping stone for series production vehicles. Secondly, and in fact even more convincing, is the manner in which Audi came to work on the DCT technology for its rally quattros: by a lucky coincidence of an influential decision maker–Ferdinand Piëch.

The most interesting aspect of the emergent sequence deployed by VAG is actually the way it leveraged the influence of factors other than niche strategies, i.e. external factors. The initial 'demo, experiment and develop' was not particularly helpful in improving the reliability of the product. For its later introductions, VAG eluded the use of niche strategies to mitigate the technological deficiencies, and turned to 'internal' and 'external' R&D. Their effect on the 'new high-tech product' and 'production system' was significant, since the two barriers were completely removed as a result. In fact, Volkswagen AG needed to use niche strategies aimed at social core factors, perhaps because these were the most impactful under the particular market context.



Despite the fact that at the time of writing Porsche is part of Volkswagen AG, the reader is advised to note that this happened several years after the large-scale diffusion hallmark, i.e. after the time period for strategic niche introductions had phased out. Therefore, Porsche cannot be said to have introduced the technology via a series of niche strategies, since the minimum requirement for at least two subsequent niche strategies was not fulfilled. However, had Porsche introduced the PDK on the commercial 969 model, shortly after the racing niche, it would have commanded further investigation of a presumably deliberate sequence. In absence of such a situation, this discussion is limited to hypothetical inquiries.

5.D Why did a sequence of niche strategies – if any – emerge during the market adaptation phase?

The barriers to large-scale diffusion can be regarded as the reason for the emergence. From this perspective, the sequence of niche strategies arose because of the changing market context between the two product introductions.

The sequence can prove useful in a situation when technological barriers are found to be more prevalent earlier on in the market adaptation phase, and societal barriers later; and the different niche strategies are targeted exactly at that type of barriers. In fact, it could be extrapolated that a more far-reaching logical sequence would be one where niche strategies are initially targeted at technological barriers, and thereafter at social barriers.

5.E Based on which criteria did companies opt for a wait-and-see, niche or large-scale introduction strategy?

Volkswagen can be considered to have introduced the technology in a niche market in order to remove the remaining barriers to large-scale diffusion. Given that the production facility was ready by 2003, they could have opted directly for a large-scale introduction in consumer diesels, but they did not.

Porsche had the knowledge and the means to introduce an early version of the technology to the consumer market, but opted against doing so. Given that they finally introduced the PDK around the late 2000s, it begs the question of whether they used a wait-and-see strategy. The case evidence is largely in support of them having –temporarily– abandoned the technology altogether; rather than monitoring the market-place for the perfect period to (re-)introduce it, on the basis of the following two arguments. Firstly, Porsche and ZF began their collaboration on the design and development of the PDF in 2003 (Sherman 2012), around the same time when VW had already demonstrated the technology potential. Secondly, it took Porsche and ZF more than four years after the actual sales take-off to ready the PDK for its consumer market introduction (see Andropoulos 2015), meaning that the product was far from completely developed. Therefore, Porsche's introduction of the PDK in a consumer market resembles to a competitive response, rather than a wait-and-see niche strategy.

5.1.6.CONCLUSION

6.A How do the case results contribute towards answering the research questions?

Table VIII is meant to summarize the outcomes of the case which contribute towards answering the research questions formulated at the beginning of the current thesis report. The descriptions from the right hand-side column are based on conclusions drawn in the previous sections.

Table VIII: Preliminary answer to research questions based on the DCT case results

Research question	Preliminary answer
1.What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?	The methodology proposed under section 4.4 proved well-suited for the investigation of sequences of niche strategies.
2.How do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	Technological barriers were prevalent during earlier periods of the market adaptation phase, whereas social barriers had the tendency to appear during or later in technology life cycle. The social barrier of 'customers' was the last to disappear. Secondly, technological barriers tended to dominate for approximately the entire length of the market adaptation phase, whereas social barriers proved to be more erratic.
3.Why do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	The change in the barriers can be explained by three main aspects: (1) external factors; (2) niche strategies introduced or removed certain barriers to large-scale diffusion; and (3) the change from one market to another –for e.g. from racing to a consumer market– influences the manner in which barriers are interpreted.
4.Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?	The case supports the claims by Ortt et al. (2013) that a large-scale introduction strategy is a possibility once there are no more barriers to large-scale diffusion; conversely, niche market strategies represent an option for managers willing to introduce products while diffusion is still hampered. For Volkswagen AG, the production facility was ready by 2003, so they could have decided for a large-scale introduction in consumer diesels. However, they opted for 'geographic' niche strategy and 'educate and experiment' niche strategy to address the core factor of 'customers'. In addition, the case showed how niche market strategies can prove effective in removing the social barrier of 'customers'.
5.What could be the logic and rationale behind sequences of niche strategies for market creation?	Emergent sequences of niche strategies can appear due to (1) the changing market context over the market adaptation phase.
6.What are logical sequences of niche strategies in the selected industry?	For this particular automotive case, the logical sequence of niche strategies would be one in which technical barriers are initially

	targeted, and thereafter social barriers: 'demo, experiment and develop', followed by 'educate' and 'geographic'.

In conclusion, the case on the DCT technology was helpful in answering the research questions.

6.B What are the theoretical implications of the case results?

Firstly, the conceptual model presented in section 3.2, is supported by the DCT case. The external factors – autonomous developments in other industries, internal R&D, economic downturn– were influential in either creating new barriers or removing the existing ones, as shown by the arrows in light red featured under Figure 23.

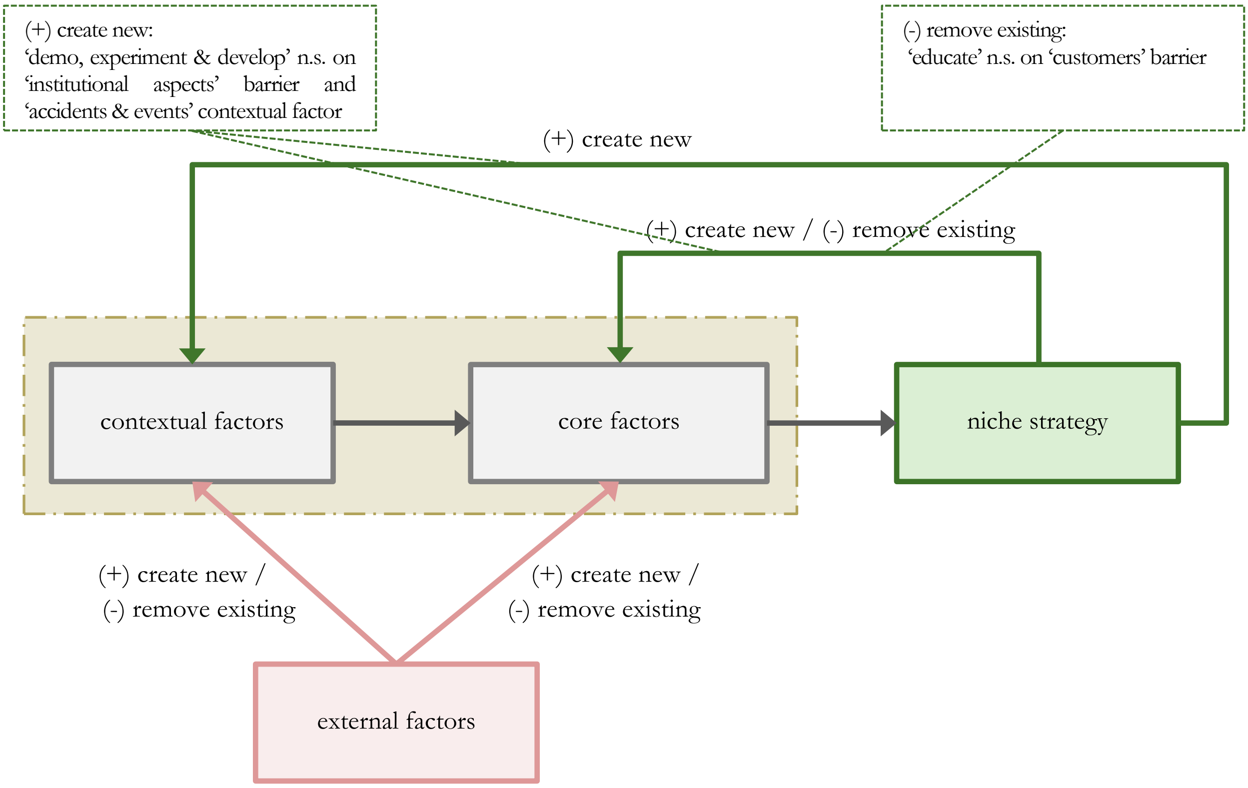


Figure 23: Conceptual model – DCT technology

Secondly, the hypothesized influence of niche strategies on the barriers to large-scale diffusion was confirmed. More specifically, the 'demo, experiment and develop' niche strategy was instrumental in creating a new barrier, whereas the 'educate and experiment' was effective in removing existing barriers.

In terms of the theoretical additions to the model, an interesting observation arises when looking at the price commanded by the vehicle manufacturers for sporty models from 2003. The DCT option was initially available on the top range models alone, therefore the central actor commanded a price premium from customers willing to adopt the technology. This situation would hint at the top niche strategy approach, but the corresponding market situation for this particular strategy was not active anymore. So, it would be wrong to conclude that the central actor had (also) used a 'top' niche strategy.

In fact, another interpretation is more appropriate to the stated facts: the ten niche strategies can elicit or borrow certain characteristics of fellow counterparts. For instance, the 'educate and experiment' niche strategy or the 'geographic' niche strategy was used in combination with a price premium. These niche strategies should not be regarded as individual blocks to be used by managers; but rather as hybrid strategies which can present characteristics of several niche strategies.

For the specific case of the DCT technology, a hybrid 'geographic-top' niche strategy is likely to have been used. The European drivers were willing to pay a higher price for the adoption, given that the technology offered the best of both worlds: fuel economy –which was a prevalent socio-cultural aspect in Europe at the time– and very fast gear changes. In the case of a hybrid 'educate-top' niche strategy one would have to argue that customers were willing to pay a premium for the technology based on their lacking understanding of the product's benefits. Framed in this way, the logic would not support the claim.

Lastly, the pattern of development and diffusion presented an interesting observation. After the cancelled product introduction by Porsche –and the previous withdrawal from racing– approximately one decade passed until sources mentioned the resumed work on the transmission. Furthermore, BorgWarner appears to have invested considerable efforts in furthering the knowledge on the technology. These two observations hint that the period of ten years bared more resemblance to the earlier innovation phase, rather than the alleged market adaption. In simple terms, it would appear as if manufacturers returned to the drawing board instead of experimenting with the product in the market; the knowledge of the technology was simply not sufficient for a reliable product.

This has a theoretical implications for the model posited by Ortt & Schoormans (2004). The position of the different phases need not be regarded as fixed, but in fact they are better interpreted as building blocks of the technological life cycle.

6.C What are the managerial implications of the case results?

The introduction by Volkswagen AG highlights how niche markets can be used to create a large-scale market: the introduction in sport cars paved –and accelerated– the way to the broader market of consumer diesels. This is in line with DeBresson (1995), who argued that niche markets can be regarded as transition paths towards mass markets. The case also shows that niche strategies should be considered in view of a future large-scale introduction, as Volkswagen appears to have used a sequence of niche and large-scale strategies very successfully.

Secondly, and also one of the most interesting implications, the removal of barriers can be done via the coupling of (sequence of) niche strategies and external factors. Volkswagen leveraged the influence of the 'educate' niche strategy on the social barrier of 'customers', after having successfully removed the hampering effect of the 'new high-tech product' core factor via 'internal R&D' and 'external R&D'. To put it succinctly, the external factors –and primarily 'internal R&D'– altered the market context such that the strategies made sense to begin with.

Lastly, a word of caution is order for managers wanting to introduce radically new high-tech products via niche strategies. One of the key findings of the case relates to the uncovering of the fact that 'demo, experiment and develop' niche strategy –and perhaps others as well– can directly influence the creation of new barriers; more specifically 'institutional aspects' for DCT. This entails that niche strategies can sometimes provoke more harm than good. The decision to introduce a product via a niche strategy should weigh in the potential negative influences on the barriers to large-scale diffusion.

Viewed from a different perspective, companies can also leverage this newly identified influence to catch-up on or hinder more technologically advanced competitors. Lagging market players can introduce the product in the market with the intention of changing the market context in such a way that competitors cannot exploit their technological leadership.

5.2. CASE 2: ANTI-LOCK BRAKING SYSTEM (ABS)

5.2.1. INTRODUCTION

During heavy braking in particular weather and road surface conditions such as "wet or icy roads, it is very easy for the driver to inadvertently lock the wheels. When this happens the car starts slipping […], and stopping the vehicle takes much more time and effort." (Veloso & Fixson 2001, p.248)

The functionality of the anti-lock braking system –henceforth ABS– is that it "prevents wheel lock during full braking. [For automobiles t]his ensures that the vehicle can still be steered and moved out of the way of unexpected obstacles." (Robert Bosch GmbH 2003a). To achieve this functionality the technology relies on comparing the speed of deceleration of the wheels, and if "the brakes are being applied and one or more of the monitored wheels suddenly begins to reduce speed at a higher rate than the others—indicating a loss of traction with the road and an imminent wheel lockup and skid—the controller then activates the antilock system." (Joel 1996) This activation entails that the brake pressure is reduced until the respective wheel(s) is(are) no longer slipping. "As long as the brakes are not being applied and all of the monitored wheels are rotating at roughly the same speed, the system takes no action." (Joel 1996)

Prior to the diffusion of ABS, skilled drivers used to avoid such situations by "rapidly pumping the brake pedal, repeatedly taking the wheels to the point of locking and then allowing them to roll again. This technique, called cadence braking, requires a high level of skill and concentration under panic conditions, far from the ability of an ordinary driver." (p. 248)

In fact, the idea to automate cadence braking –which eventually concluded in the development of ABS technology– had existed for several decades (Veloso & Fixson 2001). In 1908, "J.E. Francis presented his 'slip-prevention regulator' for rail vehicles" (Robert Bosch GmbH 2003b, p.31). Unfortunately, it is not clear whether this date corresponds to when the technological principle had been also demonstrated; for instance had a working artefact been created? It could also be the case that 1908 was only when the idea was conceptualized. Sources either contradict each other or are too vague to accurately identify the first demonstration of the technological principle, which is a requirement of the invention hallmark.

After 1908, there were other inventors attempting their luck at mastering the principles of ABS: Gabriel Voisin experimented in the 1920s –sources mention two dates: 1920 (Lawes 2014) and 1929 (Levine 2014)– with a system that "modulated the hydraulic braking system pressure on his aircraft brakes to reduce the risk of tyre slippage" (Lawes 2014), but it is not clear whether the experiment worked; Karl Wessel patented his 'brake-power regulator' in 1928, "but the design existed only on paper" (Daimler Communications 2008); as ineffective as Wessel's design were Möhl's 'safety device for hydraulic brakes' and Richard Trappe's 'brake-blocking preventer' (Robert Bosch GmbH 2003b, p.31); in 1936, Bosch filed a patent application for an 'apparatus for preventing lock-braking of the wheels of a motor vehicle' (Robert Bosch GmbH 2003a), "but again the system did not go beyond the concept stage" (Lawes 2014). Then, in 1941 an anti-lock regulator was tested which achieved modest success (Daimler Communications 2008). This later instance should mean that the invention had materialized, and thus the technological principle had been demonstrated.

Hence, since the exact year for the demonstration of the technological principle cannot be precisely identified, the time interval 1908 – 1941 would have to suffice as the invention hallmark. Although there is a large variance in pinpointing this hallmark, for the scope of the current research, this aspect does not impact the research results. This would not have been the case for a large variance of the first market introduction or of the large-scale diffusion hallmark.

By the same year –1941– the Handbook of Automobile Technology could only summarize the situation around the development of ABS as follows: " '[a]ttempts to combat the danger of blocked brakes by means of devices have, so far, only achieved very modest success.' "(Robert Bosch GmbH 2003b, p.31)

There are three main components in an anti-lock braking system: wheel speed sensors, control unit, and system modulator (adapted from Nunney 1992). The sensors are responsible for measuring the speed of the wheels, with the signal being transmitted to the control system. The information contained in the signal can be transmitted mechanically – as done on earlier models– or electronically –in the case of the more modern systems. The purpose of the control unit is to "detect any significant slow-down of wheel speed relative to vehicle speed, which could result in the braking force at any wheel exceeding the available tyre to road adhesion force" (Nunney 1992, p.573). It essentially 'translates' –independently of the driver's action– the information from the sensors into commands for the system modulator. These commands represent "valve-based sequences that modulate either hydraulic or pneumatic pressure in the individual brake lines" (p.573). This process of modulation "can simply mean holding the line pressure constant or, if further correction is required, momentarily relieving and then restoring it" (p.573). For a more detailed description of the working principles and main components of the ABS technology, particularly for automobiles, interested readers can consult the work by Nunney (1992).

5.2.2. CHRONOLOGY OF STRATEGIC NICHES

AVIATION

The first market application of the ABS technology was in military aircrafts –in 1947, the Hydro-Aire Mark I antiskid system was developed for Boeing B-47 bomber (Crane Aerospace & Electronics 2015)– followed by applications in civil aircrafts approximately four years later –in 1951, the Convairliner 340 was equipped with the Decelostat unit developed by Westinghouse (Smith & King 1951).

Most sources primarily refer to the Maxaret unit (see Veloso & Fixson 2001), developed by Dunlop both for military and civil aviation, when commenting on anti-skid units between the early 1950s up to late 1960s. And a less cited ABS system for aircrafts is the Ministop, which had presumably equipped a MD 315 French military aircraft (Smith & King 1953), but it's unclear whether it had ever entered production. All of the above systems were mechanical. The first electronic ABS applied in aviation was in 1967; referring to Dunlop's Mk10 Maxaret "produced under collaborative licence from the Hydro-Aire Division of Crane Corporation, USA" (Smith et al. 1967, p.847).

RAILWAY

Another market application, even earlier than 1948, might have been considered in railway vehicles. As Nunney (1992, p.572) mentions, "anti-skid control was first employed for railway braking systems by the Westinghouse Air Brake Company in America". However, there is disagreement in the literature whether these railway systems may be regarded as ABS. Barwell (1973) –among others– points out that the braking system used differs to some degree from the Maxaret system in aircrafts. Primarily, "the equipment is set so that it does not operate until the axle is slowing up at a distinctly higher rate of deceleration than that corresponding to the deceleration of the train itself. When it operates, brakes are released completely and then reapplied" (Barwell 1973, p.150). According to the definition of the technological principle provided in section 5.2.1 these critics should be given credit, because the brake pressure is not modulated until the wheels are no longer skidding, but rather it is completely released.

Nevertheless, as Nunney (1992, p.572) comments "it was in the further development of this idea and its application to the disc brakes of aircraft that this same company [i.e. Westinghouse, under the same product name – Decelostat] found the widest demands in the late 1940s." Thus, although the application in railway cannot be regarded as ABS technology in accordance to the definition provided under section 5.2.1, it appears that Westinghouse could make use of this technological know-how to develop systems for aircrafts, based on its earlier railway systems.

AUTOMOTIVE

The year of 1958 dates the first experiment of an ABS system in automotive. In that year, a Royal Enfield Super Meteor motorcycle equipped with Maxaret anti-lock brake was tested by the Road Research Laboratory (Levine 2014; Curtis 1971). "The trials revealed that anti-lock brakes may be of significant worth to motorbikes, for that skidding is included in an elevated dimension of mishaps" (Levine 2014). However, Tony Wilson-James – Enfield's technological director at the time– opted not to manufacture ABS-equipped motorcycles (Reynolds 1990).

In the same year, 1958, one source notes that "a Jaguar car, equipped with a Dunlop Maxaret anti-skid braking system, was demonstrated […] on the proving ground of the Dunlop Rubber Co. Ltd" (Commercial Motor 1966a, p.100). The demonstration was organized by Dunlop to show "that prevention of wheel locking would ensure that the vehicle did not develop a tail swing when the brakes were fully applied on a slippery surface and that the stopping distance would be materially reduced" (p.100).

Following these attempts, in the early 1960s a fully mechanical ABS technology was experimented on the Ford Zodiac, but did never progress beyond this stage (Levine 2014). Dunlop's Maxaret system was fitted on the Ferguson P99 racing car. "The P99 was extensively tested using the Dunlop system in place, but when the governing body introduced a rule changing the engine capacity by a considerable margin, the P99 was suddenly too heavy for its own good. Something had to go, and as a result the P99 only ever raced without its Maxaret system fitted" (Lawes 2014).

There were also experiments carried out on electronic ABS by researchers at Teldix GmbH, from as early as 1964. "The idea was presented to Daimler-Benz AG in 1966, and close collaboration between the two companies ensued. Comprehensive winter trials demonstrated that the product (known as 'ABS 1') worked, but the durability of its electronics left a lot to be desired" (Kuhlgatz 2014, p.55).

Lastly, in 1966, the Maxaret technology was demonstrated by Dunlop on the 12th of September 1966, "this time applied to the air-pressure brakes on the driving axle of a Leyland Beaver tractive unit hauling a laden Crane Fruehauf single-axle semi-trailer, and the purpose of the demonstration was to show that this use of the system eliminated jack-knifing" (Commercial Motor 1966a, p.100), a common road safety hazard at the time.

In the case of all these early application from 1958 up to 1966, given that there was no actual market introduction, they may only be regarded as technological niches. In fact, it was in 1966 that the first market applications of the ABS technology in automotive appeared; first mechanical, and soon-after electronic. During that year, Dunlop's Maxaret system was fitted to tractive units –the segment will be referred to as 'heavy trucks'– and passenger cars. The following description of the strategic niches will begin with the heavy trucks segment, and thereafter continue with passenger cars.

HEAVY VEHICLES

Following the demonstration from September 1966, just one month later "[t]he first of 12 […] articulated road tankers to be fitted with the Dunlop Maxaret braking system was handed over" (Commercial Motor 1966b, p.41) to Shell-Mex and BP Ltd. Initially only 500 Maxaret units were said to be manufactured, with full-scale production planned "in about two years' time following further development and refinement" (p.41).

Then, in 1969, the electronic version of the Maxaret system –Mk. IIE electronic anti-wheel-locking device– was available for fitting to tractive units (Commercial Motor 1969, p.42). The product had been developed at least 18 months earlier, when testing began. Prior to the market introduction, approximately 100 vehicles had been equipped with the product towards this aim. According to a company statement from 1969, operators could choose between an original-equipment kit priced at £120, or existing vehicle conversion for £172. For the latter, Dunlop technicians would install the system on operators' premises and also perform testing procedures. (Commercial Motor 1969)

Around 1981-82, Bosch also entered the market for trucks (Robert Bosch GmbH 2003b; Kuhlgatz 2014).

LUXURY PASSENGER CARS

The first road car to be equipped with an ABS system would be the Jensen FF –Formula Ferguson– in 1966 (Day 2014). The car featured the "Ferguson four-wheel drive system, unheard of in cars of the time, with the Maxaret system." (Lawes 2014). However, only 320 models were built from 1966 to 1971 (Koscs 2013).

All market introductions in passenger cars following the Jensen FF consisted of electronic versions of ABS: Sure-Track by Kelsey Hayes, Track Master by General Motors, Sure-Brake by Bendix, and ABS by Bosch. (Cutter 1968; Curtis 1971; Severson 2009; Kuhlgatz 2014; Lawes 2014)

Sure-Track and Track Master were rear-wheel only systems. The first, developed by Kelsey Hayes, was introduced on the Ford Thunderbird, Lincoln Continental MkIII in 1969, and the Lincoln Continental Mk IV in 1974-75 (Severson 2009; Koscs 2013). Interestingly, Sure-Track started as optional feature –at $195– on the Continental MkIII in 1969, it was then promoted to standard feature in 1970, and reverted back to optional in 1976 on the Continental Mk IV (Severson 2009). The first of Japan's ABS equipped cars was the Nissan President H150 which had anti-lock as an optional feature. The ABS unit was manufactured by Kelsey Hayes, and branded as Electro Antilock System (EAL).

Track Master was developed by General Motors (GM) or Delco –one of its vertically integrated suppliers– (Cutter 1968; Veloso & Fixson 2001) and debuted in 1970 on the Cadillac Eldorado. It was promoted as an option on the entire Cadillac line from 1974.

As opposed to GM or Kelsey Hayes, Bendix had developed a more sophisticated four-wheel anti-skid system, branded as Sure-Brake (Road Test 1971). It was sold as a $351 option on the Chrysler Imperial, in between 1971 and 1973 (Behme 1970; Severson 2009; Lawes 2014). Sources indicated that it equipped a few hundred cars per year, "probably going on less than 5 percent of Imperials through 1973" (Koscs 2013). From 1973 the technology was discontinued due to lack of interest from consumers (Severson 2009; Koscs 2013).

Bosch entered the ABS market for passenger cars in the late 1970s (Nunney 1992). The first model to be equipped with Bosch's –second generation– ABS was the Mercedes-Benz S-Class W 116 around October-December 1978 as an optional feature for DM 2,217 (Daimler Communications 2008; Day 2014; Kuhlgatz 2014). In December of the same year it was introduced on the BMW 7 Series, also as an option (Robert Bosch GmbH 2003b). From 1984-1985 it became standard on all Mercedes-Benz passenger cars (Daimler Communications 2008), and on BMW's 7 Series, 6 Series, and M535i models.

All of market introduction in passenger cars described above correspond to the luxury cars segment. The first, Jensen FF, was essentially a Grand Tourer (GT) which embodies both performance and luxury. The American cars of the early 1970s could be best ascribed to the personal luxury car segment. The later vehicles from 1978 correspond to the high-end luxury class. In fact, up to 1984-1985 the ABS technology had been introduced only in the segment of luxury cars.

SUMMARY

The niche applications of the ABS technology were as follows: military aviation, civil aviation, and simultaneously heavy vehicles and luxury cars. Figure 24 presents this schematically.

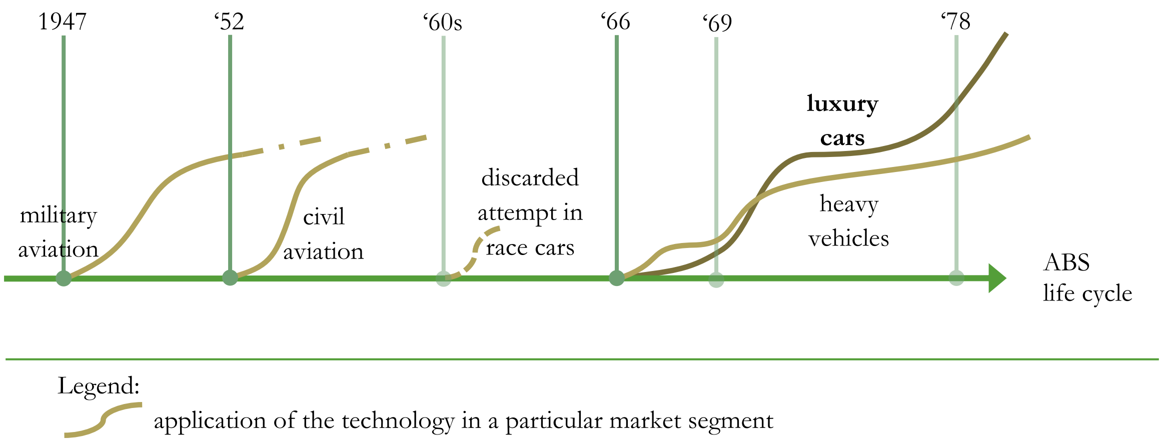


Figure 24: Graphic depiction of applications of the ABS technology in particular market segments

Sources primarily indicate that the uptake of the ABS market can be attributed to Bosch: "beginning with the introduction of the Anti Blockier System (ABS) in 1978 by Robert Bosch working in conjunction with Mercedes-Benz, that the development of anti-lock braking systems started in earnest and has led to their increasing adoption" (Nunney 1992, p.572). By 1981, ABS units manufactured by Bosch had already been fitted on 100,000 vehicles (Robert Bosch GmbH 2003b). In 1986, one million ABS units had been supplied by Bosch (Robert Bosch GmbH 2003a; Robert Bosch GmbH 2003b; Kuhlgatz 2014). Given that there were other prior market introductions by several other manufacturers –either in aviation or automotive– the one millionth ABS unit in the world had most likely been produced prior to 1986. On the basis of the case literature, the early 1980s will be considered as the hallmark for market stabilization, since it was around that time that the market for ABS started to diffuse on a large-scale.

Following mass-market diffusion, the technology was also introduced –by Kelsey Hayes in 1987, and Bosch around 1988-1994– in motorcycles, non-premium passenger cars, or light trucks and buses. By the mid-1980s, ABS had become a standard specification on heavy commercial vehicles and coaches in Europe; and in 1991 it became a mandatory requirement. (Day 2014) Since 2004 all new cars sold in Europe were required to have ABS as standard (Kuhlgatz 2014).

For the visual representation of the complete pattern of development and diffusion, interested readers are directed to Appendix 3: Patterns of development and diffusion.

5.2.3. CHRONOLOGY OF NICHE STRATEGIES

Similar to the previous case report, before presenting the barriers which were found to hamper large-scale diffusion, it is worthwhile to comment on those barriers which were absent. Firstly, the core factor related to complementary products and services was not encountered. To quote one of sources, originally referring to Dunlop's Maxaret system for aircrafts, ABS was a "'fit and forget' system" (Ramsden et al. 1975, p.607). Given the modularity of ABS technology (see Veloso & Fixson 2001), the comment can be extrapolated to cars as well. Nonetheless, the system had to be complementary to the existing regime as a sub-system component of a vehicle's

–i.e. aircrafts, trains, automobiles, etc.– braking system. In the author's view this aspect is fundamentally different than the description of the core factor 'complementary products and services' as defined by Ortt et al. (2013).

Secondly, institutional aspects did not block the adoption of ABS. Rather, as presented later under section 5.2.4, the regulatory environment –at best– could be considered responsible for speeding up the diffusion.

1947-1954

Cutter (1968, p.105) notes that prior to the late 1950s, "[w]hile antiskid devices have been dreamed about for years […] there was little or no practical progress because they [i.e. engineers] couldn't agree whether skidding was a help or a hindrance in stopping a car." Many engineers were of the belief that the maximum deceleration occurred during tire skidding. This meant that the lacking knowledge of the physical principles –represented by the contextual factor 'knowledge of the technology'– influenced the core factor 'new high-tech product', in the sense that the benefits of a Maxaret-type of system in automotive were not clear to begin with.

For aircrafts on the other hand, "[w]heel-lock can be difficult or impossible to detect from the cockpit, and causes very rapid tyre wear" (Ramsden et al. 1975, p.607) Furthermore, "[w]ith an aircraft the objectives are to prevent at least expensive tyre damage and at worst a potentially dangerous tyre burst, by avoiding wheel locking however briefly it may occur during maximum braking through the landing run" (Nunney 1992, p.572). This meant that the ABS technology could have been applied in aircrafts without necessarily mastering the technological principle completely. The 'technological redesign' niche strategy corresponds to this market situation. However, as opposed to the description by Ortt et al. (2013), the product was not necessarily introduced in a simpler version –if considering the complexity of the system– but rather merely in a version that could be produced within the existing knowledge of the technology.

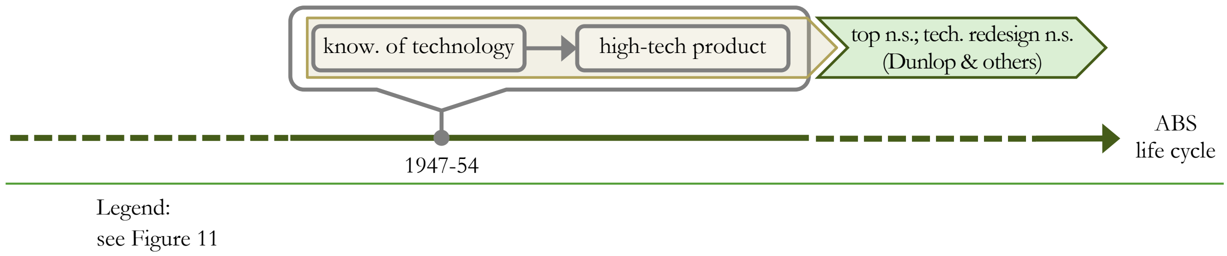


Figure 25: Market context of the ABS technology between 1947-1954

When the first experimental ABS systems for cars emerged in the early 1960s, their price proved prohibitive (Levine 2014; Curtis 1971). Implicitly, this was likely to have been the case a decade earlier, when ABS was introduced in aircrafts. Thus, on the basis of the same market situation mentioned above, the companies targeting the niche market of aviation in the late 1940s and early 1950s would have likely introduced the technology via a 'top' niche strategy.

With regard to the market actors, it is interesting to note that initially the British "Ministry of Supply wanted urgently to investigate anti-skid techniques and pressed Dunlop to take out a patent to licence-build an American unit" (Ramsden et al. 1975, p.607) from Hydro-Aire or Westinghouse. However, Dunlop's technical director –Trevaskis– "evolved an ingenious device to prevent wheel slip" (p.607), which became the Maxaret device. Dunlop also opposed to rely on Government assistance, and therefore developed the system with private money (Ramsden et al. 1975). Despite this development would resemble to the external factor 'internal R&D' from the earlier case study, this situation is different. Although Dunlop's product was the most popular –at least according to the number of literature references– it was not necessarily more technologically advanced or more reliable. Therefore, Dunlop's internal R&D can be considered to have helped them develop the product, but not necessarily improve the knowledge of the technology or the new high-tech product itself.

Westinghouse, on the other hand, as detailed in section 5.2.2, appears to have leveraged the technological know-how accumulated via the similar ABS system for railway vehicles, and applied it to develop the Decelostat for aircrafts. Quoting Nunney (1992, p.572) again, "it was in the further development of this idea and its application to the disc brakes of aircraft that this same company [i.e.. Westinghouse] found the widest demands in the late 1940s." Similar to the Dunlop argument, Westinghouse's research and development efforts did not necessarily improve the knowledge of the technology or the high-tech product, therefore it makes no sense to feature it as an external factor.

1958- 1964

Between 1958 and 1964 there were several attempts at introducing ABS technology to automotive, but without an actual market introduction. Towards the late 1950s "a group of British engineers arrived at the […] conclusion that maximum retardation could be achieved with a 15 percent skid" (Cutter 1968, p.105). This meant the technological principle had become better understood, in part due to the efforts in aeronautics –as featured under Figure 26 by the influence of the niche strategies on the barriers– but also because of the experiments with motor vehicles – i.e. 'R&D'. External R&D refers to the earlier mentioned group of British engineers; their contribution was in advancing the technological principle, not in developing the high-product. Internal R&D refers the work performed by the National Research Laboratory with Dunlop's cooperation, which had an impact on both factors featured in Figure 26.

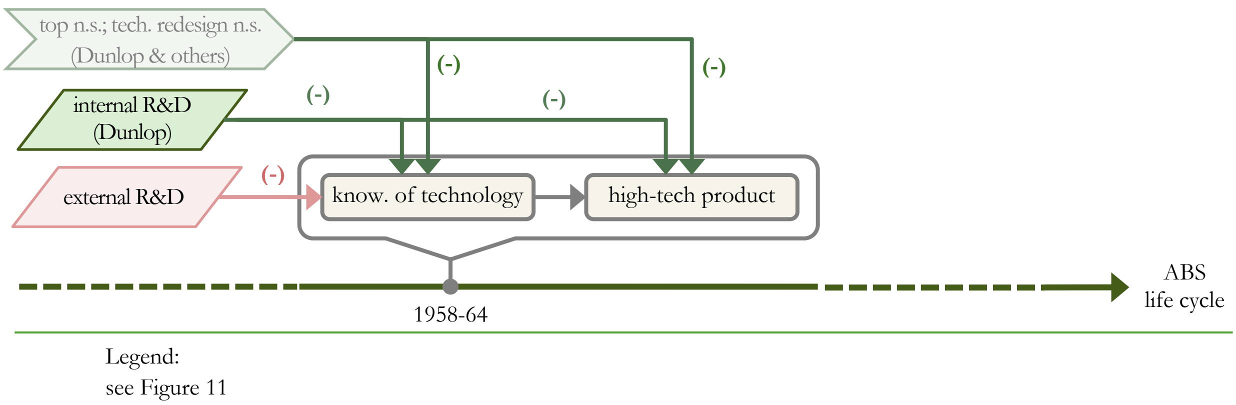


Figure 26: Market context of the ABS technology between 1958-1964

However, with the shift from aircraft to passenger cars, the requirements from the ABS unit had changed. "In comparison with an aircraft tyre, the tyre of a motor vehicle is relatively lightly loaded and […] what is really important is any loss of directional control or stability" (Nunney 1992, p.572). For passenger cars, "the demands on the mechanical friction wheel sensors were much higher: they had to register decelerations and accelerations in wheel speeds, they had to react reliably in corners and on rough ground and work perfectly even when heavily soiled and at high temperatures" (Daimler Communications 2008). Furthermore, as proven on the Ford Zodiac and the Ferguson P99 rally car, the new high-tech product was "costly undependable" (Levine 2014). Therefore, in between 1958 and 1964 the new high-tech product did not offer a good price/quality, and therefore large-scale diffusion was hampered. At the basis of the above issues was the lacking knowledge of the technology.

Without having proven reliable, the mechanical ABS systems were not ready to be used in trucks as well; despite the great benefits: reducing tyre wear, or addressing the problem of jack-knifing.

1964-1966

Prior to the Jensen FF, a "fundamental problem was to find a way of relieving and restoring the pressure in a conventional hydrostatic braking system without the recourse to the alternative of fully powered braking" (Curtis 1971, p.359). Ferguson had solved the problem with "their ingenious double-sided vacuum servo" (p.359). Another potential technical resolution was to bleed part of the hydraulic fluid from the system, and then –by using a small electric pump– restoring it. This latter configuration was used by Teldix on the Mercedes-Benz (Curtis 1971). It can be concluded that this potential hampering issue with the new high-tech product was first resolved by Ferguson with their ingenious design in 1966. Therefore, prior to 1966 it would have hampered the diffusion of the innovation.

In the early 1960s the semiconductor technology "created the preconditions for the necessary rapid triggering of the [ABS] system" (Robert Bosch GmbH 2003b, p.31). While it became apparent that electronically controlled ABS units were feasible, "their development involved such immense financial investment that their use was virtually limited to aircraft and express trains" (p.31). Therefore, the core factor of 'suppliers' would have likely hampered diffusion due to the high capital cost during this period. The contextual factor is featured in Figure 27 as 'financial resources'.

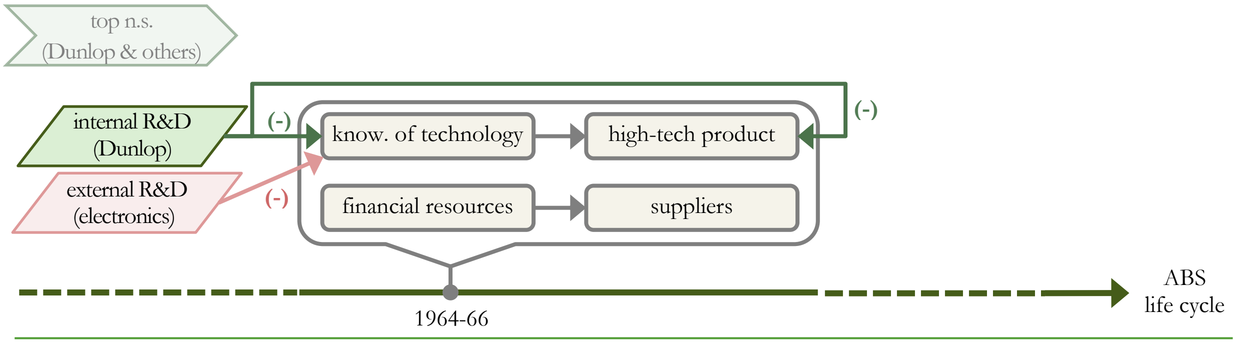


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Figure 27: Market context of the ABS technology between 1964-1966

1966

In 1966, the Jensen FF was introduced, and as argued earlier the knowledge the technology with regard to the way of restoring and relieving pressure in the system had been advance. As opposed to the earlier versions of the Maxaret system this was "[a] much simpler system, requiring only one Maxaret unit to operate all four wheels" (Starks 1968, p.9). This would hint that engineers had also addressed the problem of poor reliability, by reducing the degree of complexity of the system. This niche strategy can be seen as 'technological redesign', whereby the product complexity was reduced and therefore the reliability of the system was increased. The influence of the niche strategy on the 'new high-tech product' barrier is shown in Figure 28.

Regardless of the potential cost reductions, it was clearly not enough for a mass market. Starks (1968, p.10) reports that "[t]he disadvantages of the Maxaret [on the Jensen FF] system are likely to be its cost and complexity." Therefore, although the system had been redesigned, it was still too complex and costly for passenger cars. The Jensen FF was essentially a low volume production car, with only 320 units ever built (Koscs 2013). Furthermore, as a Grand Tourer, it was very expensive. Therefore, given the characteristics of the Jensen FF, Dunlop introduced the ABS system to the automobile market via top niche strategy.

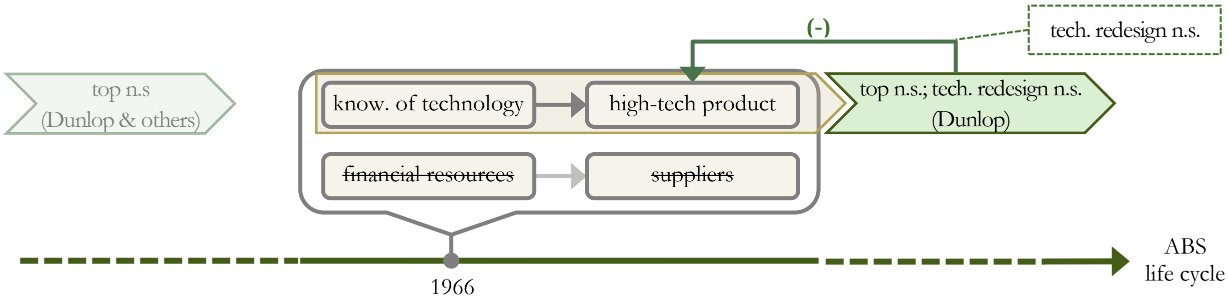

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Figure 28: Market context of the ABS technology around the year 1966

A similar rationale as above can be used for the market introduction in heavy trucks by Dunlop, where only 500 tractive units are said to have been equipped with the mechanical Maxaret system, presumably also redesigned. The major difference, perhaps, lies in the reason value proposition for the customers, which in the case of trucks were road safety and tyre wear; the latter would translate in visible cost savings for truckers.

In 1966, the core factor related to 'suppliers' had likely disappeared. On one hand, electronic ABS prototypes were already capable of reducing stopping distances, thereby indicating suppliers had become interested in experimenting. On the other hand, suppliers and automobile manufacturers –Teldix GmbH with Daimler Benz; Chrysler with Bendix– had even begun collaborating on developing such systems. Lastly, as Curtis (1971, p.359) notes, "all the numerous experimental systems announced since the Jensen FF came on the market have been electronic in operation."

1967-1969

Critics claimed that "the system lacked sufficient rapidity of response to cope with a wide variety of surfaces" (Curtis 1971, p.359). Therefore the lacking knowledge of the technology was still impacting the quality of the high-tech product, and thereby hampering large-scale diffusion. Other critics argued that while there was some improvement in the stopping distance in the wet, on dry conditions the distance was actually increased (Curtis 1971). These critics would have likely had an impact on the public view over the ABS technology, in the case of the Jensen FF at least. This is most proximate to the contextual factor 'accidents or events', which can be seen to have impacted the customers willingness-to-pay for adoption.

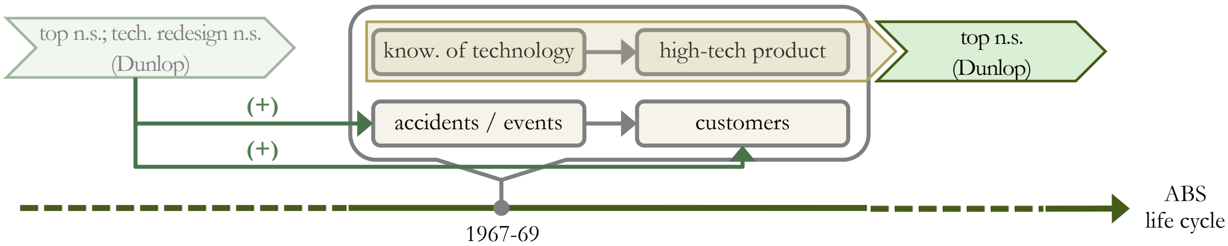

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Figure 29: Market context of the ABS technology between 1967-1969

Case evidence suggested that in 1967 Dunlop introduced the electronic Maxaret system on aircrafts. The 'top' niche strategy is logically regarded to have been used. Firstly, the same rationale as the introduction from the early 1950s can be applied. Secondly, sources already mentioned that, in the early days of electronically controlled ABS units, "their development involved such immense financial investment that their use was virtually limited to aircraft and express trains" (Robert Bosch GmbH 2003b, p.31).

1969-1976

Although not directly successful in accelerating the diffusion of ABS, the Jensen FF did have an impact on the efforts of other vehicle manufacturers. "Shortly after the Jensen's introduction, Ford Motor Co. started a hard drive toward antiskid. During the past summer, Ford staged an informal antiskid competition asking all interested suppliers to demonstrate their hardware" (Cutter 1968). One of the suppliers present was Kelsey Hayes, which will later introduce the Sure-Track rear-wheel anti-skid system in collaboration with Ford. However, this cannot be considered a 'demo, experiment & develop' niche strategy, because no direct revenue was derived by Ford –the organizer– as result of the demonstration.

Conversely, there is information that in 1968 Kelsey Hayes had built more than 100 prototypes which were being tested by automakers (Cutter 1968). This would implicitly include the vehicle manufacturer Ford. At first sight Ford can be regarded as the customer of the ABS unit which was in lack of the necessary knowledge of the technology. This would imply that Kelsey Hayes had used an 'educate and experiment' niche strategy to circumvent this market situation, with revenue to be received from featuring Sure-Track on Ford vehicles. However, Ford lacked the know-how on the manner in which to produce the high-tech product. The lacking knowledge of the technology impacting the core factor 'customers' relates to the knowledge required to use the product, which is different than the situation presented before. Therefore, Kelsey Hayes did not make use of an 'educate & experiment' niche strategy. Instead it merely initiated a collaboration with auto-manufacturer Ford by demonstrating its products.

When the electronic ABS units came to the luxury cars market around the late 1960s, suppliers were split between rear-wheel systems and all-wheel systems. "Kelsey's [Hayes] system is fundamentally a rear-wheel unit. Kelsey's engineers feel it's most important to move into this field slowly with a simple, low-priced system that will prevent rear-end slewing. […] By contrast, Bendix thinks that the front-end antiskid should be included in the system because it would provide the all-important steerability and because most of the braking in a panic stop is done by the front brakes" (Cutter 1968, p.206).

As a result, the Sure-Track system developed by Kelsey Hayes –and found on the Lincoln Continental Mk III or Ford Thunderbird– was at almost half the price of the Sure-Brake –introduced on the Chrysler Imperial; interestingly, ABS cost less than other optional features on the Imperial, such as AM/FM stereo with tape player– offered by Bendix (Koscs 2013). In contrast, Bendix' system was more effective (Severson 2009).

Rear-wheel systems were also said to be favoured by U.S. vehicle manufacturers, given their belief "that the first step should a low-cost, simple unit" (Cutter 1968, p.206). That would certainly appear to be the case if counting by the number of brands offered with rear-wheel ABS units –Lincoln, Ford, Cadillac– versus all-wheel units –Chrysler– in between 1969 and 1976 in the U.S. In contrast, these systems were "not highly regarded by the majority of the European observers because they g[a]ve little to no reduction in stopping distance and cannot prevent the ability to steer from being lost when the front wheels lock-up" (Curtis 1971, p.360). Another proof of this preference was the fact that Teldix –and later Bosch– were working on the all-wheel ABS system in collaboration with European vehicle manufacturer Mercedes-Benz.

In all of the circumstances above, it becomes apparent that the knowledge of the technology impacted the quality/price ratio with which the new high-tech product could be provided. To circumvent this market situation, some manufacturers –such as Kelsey Hayes or GM– opted for a 'technological redesign' niche strategy, and therefore reducing the technological complexity and price; but also the performance. In contrast, Bendix was not keen on sacrificing the performance, and therefore had to make due with larger costs, thus opting for a top niche strategy.

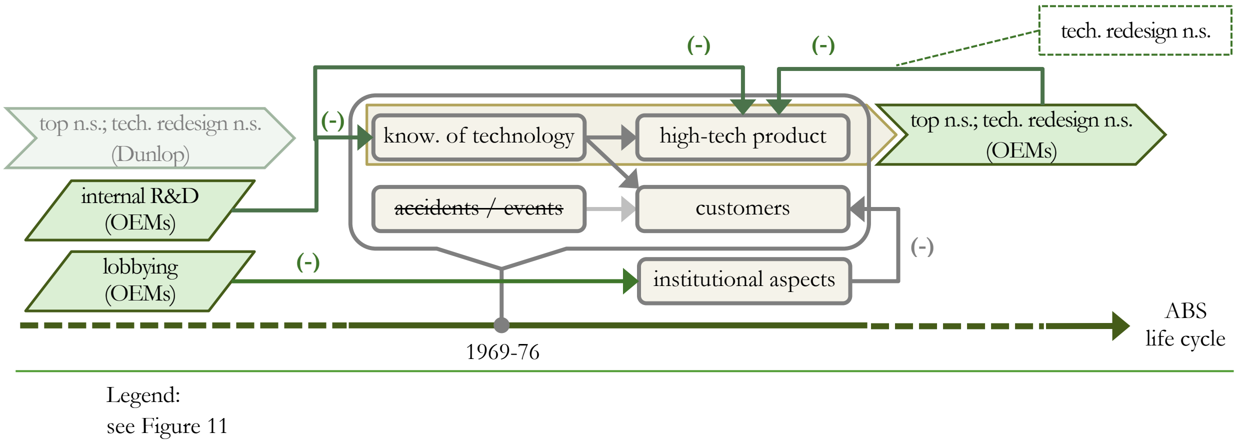

Figure 30: Market context of the ABS technology between 1969-1976

However, in their marketing efforts, "the manufacturer and its dealers probably failed to adequately market the technology and explain its benefits to customers" (Koscs 2013). Only a few hundred Chrysler Imperials are presumed to have been equipped with the Sure-Brake system each year between 1971 and 1974 (Koscs 2013). Actually, the optional feature was eventually dropped in 1974 due to lack of interest from consumers (Severson 2009); thereby confirming the earlier claim. Also, sources did not make any reference that Kelsey Hayes' Sure-Track system or GM's Track Master was successful in diffusing on a larger scale.

In the market segment of heavy vehicles, Dunlop continued to provide its Maxaret systems. In 1969, the electronic version of the system was introduced on tractive units. With the initial production capacity of 100 sets a week –said to be increased to four or five times that number from 1971– this would have resulted in maximum 11,000 vehicles equipped with Maxaret MkIIE between 1969 and 1971. Veloso and Fixson (2001, p.248) mention that the initial solutions of the early 1970s "proved to have poor reliability and a prohibitively high price." Therefore, similar to the case of Bendix, Dunlop had in all likelihood introduced the electronic ABS technology on trucks via a 'top' niche strategy. Nevertheless, the electronic version was at least cheaper than the mechanical counterpart: "[b]y using electronic skid-sensing, the Dunlop Co. Ltd., Coventry, says it has both improved the performance and lowered the cost of its Maxaret anti-skid system for air-braked commercial vehicles (Commercial Motor 1968, p.52).

The regulatory environment did not hamper large-scale diffusion. In fact, there were several instances when institutional aspects could be best described as having accelerated the diffusion of ABS by influencing the customer willingness-to-pay for the adoption –see influence of 'institutional aspects ' core factor on the 'customers' barrier via the grey arrow from Figure 30. Around the early 1970s there was "considerable concern in Detroit that impatient Washington safety officials will force automakers to install antiskid systems before they're fully developed" (Cutter 1968, p.105). Combined with strong competition, this has allegedly compelled some vehicle manufacturers towards ABS technology, even though initially they were not particularly enthusiastic about it (Cutter 1968). One such example might be GM, which had initially publicly dismissed the idea of anti-skid technology, but was then among the first to introduce the option on their cars. There were also "antiskid presentation […] made by some of the developers [of ABS] for the U.S. General Services Administration and the National Highway Safety Bureau" (Cutter 1968, p.206). At least in trucks their efforts were to some degree successful since "ABS was first required as a mandatory fitment in the USA in the 1970s" (Day 2014, p.386). In Figure 30 this aspect is represented by the 'lobbying by OEMs [Original Equipment Manufacturers]' factor.

However, the technology did not prove sufficiently robust and was subsequently withdrawn. Europe, on the other hand, made it a mandatory requirement, but only as late as 1991 (Day 2014).

Figure 29 also features the factor 'internal R&D' to refer to the development efforts made by OEMs in order to create a working product, i.e. advance the knowledge of the technology and improve performance and/or cost. Arguably, these efforts had started prior to 1969, but for simplicity they are featured under the same time-frame when manufacturers started introducing the products on the market via niche strategies.

1978

When Bosch came to the market in 1978 with its second generation ABS system, it was based on the efforts that had started originally with Teldix GmbH in cooperation with Mercedes-Benz as early as 1964-1966.

"After acquiring a 50 percent holding in Teldix in 1973, Bosch became involved in the project. Developers at Bosch had also been working on an electronically controlled antilock system, and the company had a wealth of experience in the area of automotive electronics – as a result of developing the Jetronic electronic gasoline injection system, for example" (Kuhlgatz 2014, pp.55–56). By 1975, Bosch had taken full responsibility for the development of ABS. It bought all outstanding shares of Teldix in 1981. (Kuhlgatz 2014)

The knowledge of the technology was no longer affecting the quality of the product, "since the components of the system had been cut to 140, [and] its micro-electronics now displayed the reliability needed in cars" (Robert Bosch GmbH 2003a). Also, there is no information that consumers' knowledge with respect to the ABS technology had hampered large-scale diffusion.

Thus, the introduction of ABS by Bosch cannot be considered as a niche strategy, since there were no barriers to large-scale diffusion in 1978. The technology was introduced on luxury cars, but there is no indication that the price of the ABS unit –not that of the car itself– was prohibitive for the mass-market.

In fact, Bosch –and its collaborators– used a wait-and-see strategy by opting not to introduce the product until it had reached the desired level of costs and reliability; which in this case refers to Mercedes-Benz luxury sedans, followed by those of BMW. Thereafter, "the system and its successors gradually found their way into all vehicle segments" (Kuhlgatz 2014, p.56).

SUMMARY

Figure 31 presents the series of market contexts and niche strategies during the market adaptation phase for the ABS technology. The reader is advised to note that the formerly explained effects of niche strategies or external factors on the core and contextual factors are also featured.

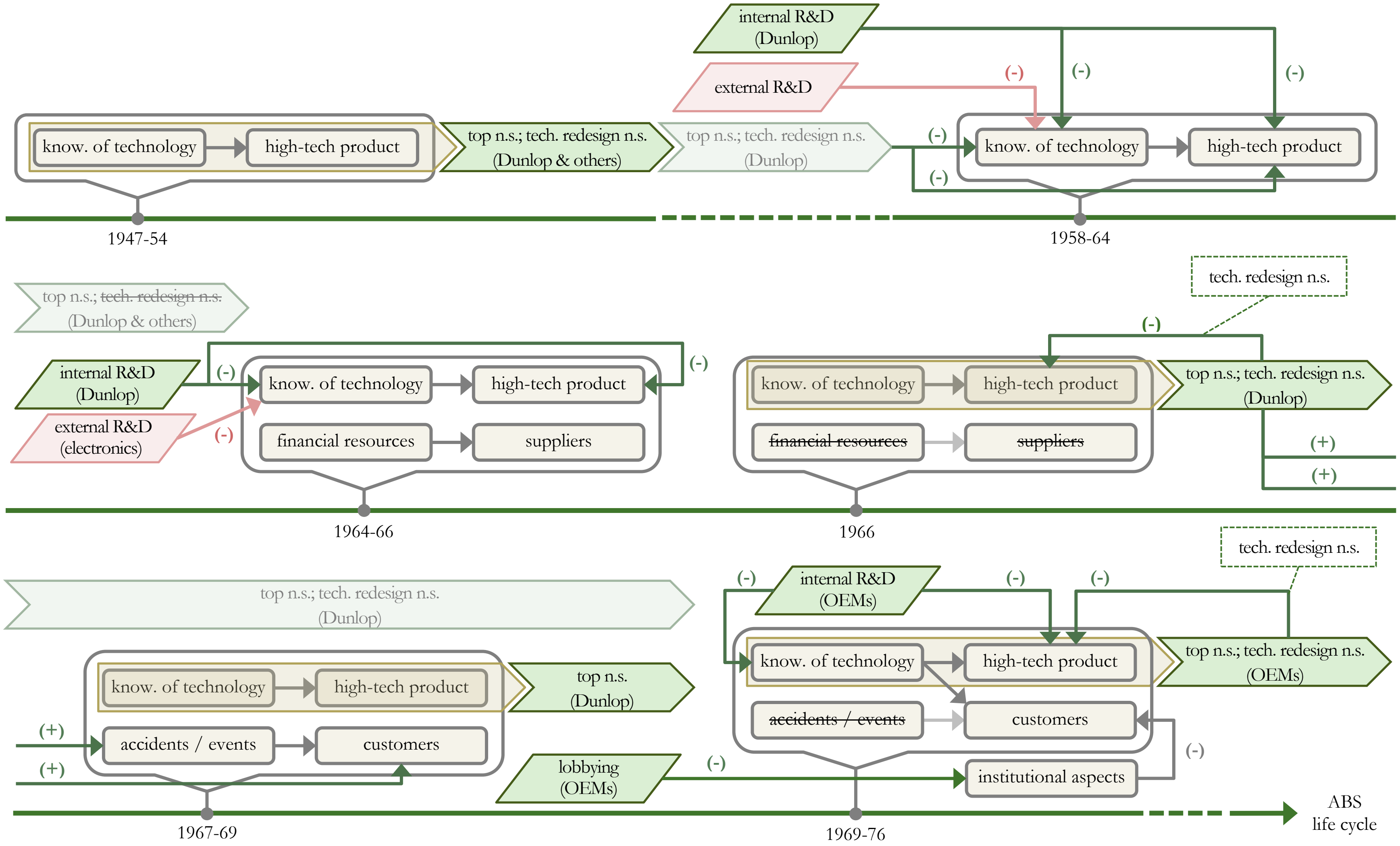

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Figure 31: Chronology of market contexts, niche strategies and external factors - ABS technology

5.2.4.CHANGE IN THE BARRIERS TO LARGE-SCALE DIFFUSION

4.A Depict graphically the change in the core factors throughout the market adaptation phase

Figure 32 depicts the change in the core factors hampering large-scale diffusion for the current ABS case. The detailed explanation of the qualitative evaluations can be found in section 5.2.3.

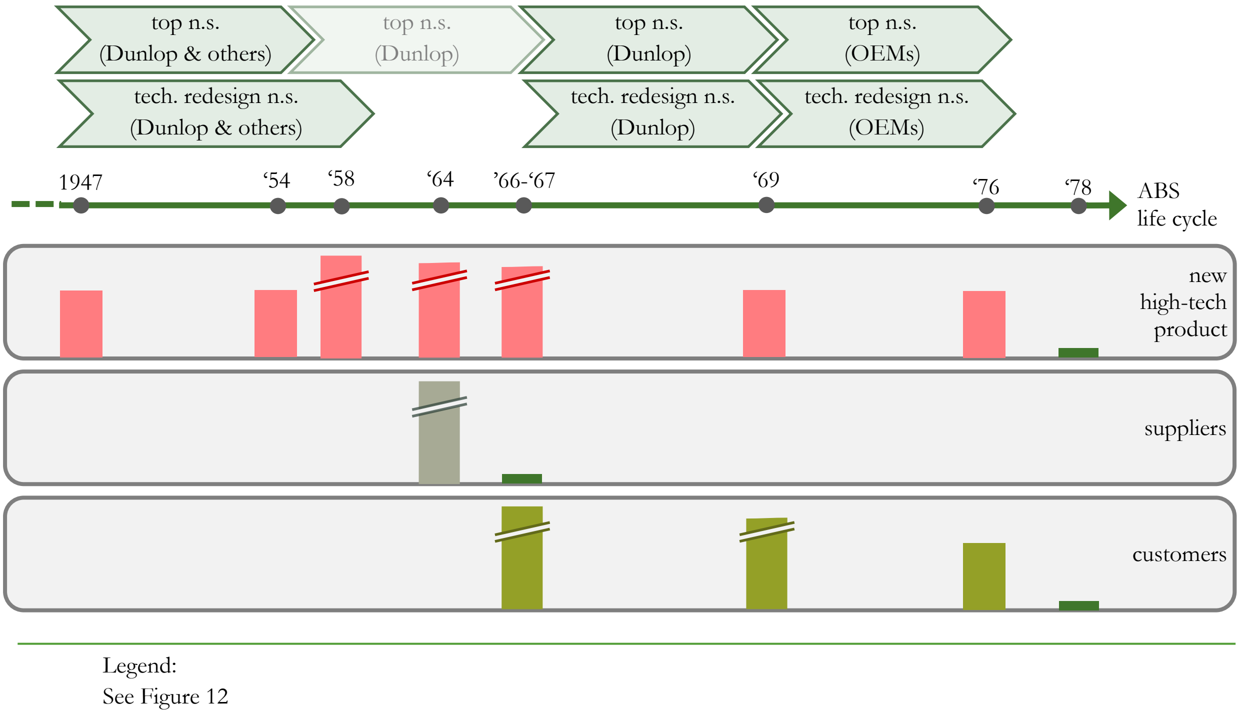


Figure 32: Dynamics of the core factors hampering large-scale diffusion – ABS technology

During the period 1947-1958 when the product had been used sold only for aircrafts, the new high-tech product was prohibitively costly. Furthermore, the state of the knowledge of the technology limited the value proposition of the ABS system to airplanes alone. After 1958, the switch from aircrafts to automotive meant that higher requirements were imposed on the high-tech product. The ABS systems would necessitate a higher speed of response, or even work when "heavily soiled and at high temperatures" (Daimler Communications 2008). The mechanical Maxaret system on the Jensen FF was both underperforming and too costly. With the switch to electronic devices in 1969, the product became more affordable (see Starks 1968); the performance was also improved, but not yet enough. The barrier would disappear with the introduction of the ABS unit from Bosch in 1978.

Secondly, the 'suppliers' barrier was an isolated and short-lived appearance in the early 1960s, triggered by the initial high investments costs required for the integration of electronic controls in the new high-tech product. By 1966 the barrier was no longer active, given that a multitude of manufacturers were already experimenting with electronic ABS systems.

Lastly, the 'customers' barrier first appeared in 1966 when the mechanical Maxaret system failed to deliver an adequate-enough performance. The barrier continued well within the late 1970s, when customers proved to be not fully aware of the product's benefits. Thus, a large portion of the customer base was uninterested and unwilling to pay of the adoption. In 1978, with the introduction by Bosch, the barrier appeared to be no longer active.

4.B How did the barriers to large-scale diffusion change over the span of the market adaptation phase?

Firstly, the 'new high-tech product' barrier hampered diffusion throughout the entire market adaptation phase. The 'suppliers' barrier on the other hand was more erratic, and remained active for a significantly shorter period of time.

Secondly, as concluded in the previous DCT case, the type of market in which a company is active can influence the strategic analysis of the market context, i.e. the manner in which the barriers are interpreted. The switch from aircrafts to automotive imposed higher requirements on the product, and the relative magnitude of the barrier increased as a consequence.

4.C What was the influence – if any – of niche strategies on the barriers to large-scale diffusion?

The early niche strategies used to introduce ABS systems in aircrafts resulted in a better understanding of the technological principle. As a result, the technology could migrate to experimental fitting on motorcycles and cars. However, this did not prove enough to remove the barrier hampering large-scale diffusion.

Secondly, the introduction of mechanical ABS on the Jensen FF led to early critics to the technology. The barrier was only temporary, and disappeared with the shift to electronic ABS.

4.D Were there any external factors – i.e. apart from niche strategies – which had an influence – i.e. remove / create – on the barriers to large-scale diffusion?

"[T]he introduction of the semiconductor technology, available from the early 1960's, […] created the preconditions for the necessary rapid triggering of the [ABS] system" (Robert Bosch GmbH 2003b, p.31). Primarily, the availability of integrated circuits gradually permitted the increase in the speed of response of the sensors. Nevertheless, in its early stages –around 1964– it also created a temporary barrier for suppliers, due to the high investment costs required.

Secondly, 'external' and 'internal R&D' by different actors played a role. 'External R&D' can be considered as that performed by the National Research Laboratory when they discovered the 15% antiskid principle, or the autonomous developments in electronics. However, note that the collaboration between the Laboratory and Dunlop was regarded as 'internal R&D'.

Lastly, lobbying by OEMs was another external factor observed. ABS developers made "antiskid presentation […] for the U.S. General Services Administration and the National Highway Safety Bureau" (Cutter 1968, p.206). In the customer segment of trucks the factor was successful and "ABS was first required as a mandatory fitment in the USA in the 1970s" (Day 2014, p.386). However, due to the low reliability of the systems this regulation was subsequently withdrawn.

4.E Why did the barriers to large-scale diffusion change over the market adaptation phase?

In conclusion, similar to the DCT case, the change in the barriers to large-scale diffusion over the course of the market adaption phase can be explained by three main aspects. First and foremost, external factors –such as autonomous improvements in the electronics industry, lobbying by OEMs, external R&D by research laboratories, or internal R&D by the central actor network– played a key role. Secondly, some niche strategies may provoke the creation of new barriers to large-scale diffusion. Thirdly, the change from one market to another –for e.g. from aviation to automotive– influences the strategic analysis of the market context, which in effect determines how the barriers are interpreted.

5.2.5. SEQUENCE OF NICHE STRATEGIES

5.A Depict visually the series of niche strategies.

The central actor is represented by the supplier –for e.g. Dunlop or Bosch– rather than the vehicle manufacturer. Simultaneously and subsequently, the 'technological redesign' niche strategy and 'top' niche strategy were used between the late 1940s and mid-1970s; initially in aircrafts, and thereafter in automotive. The subsequent niches correspond to the subsequent niche applications: first aviation, followed by luxury cars concomitantly with heavy trucks.

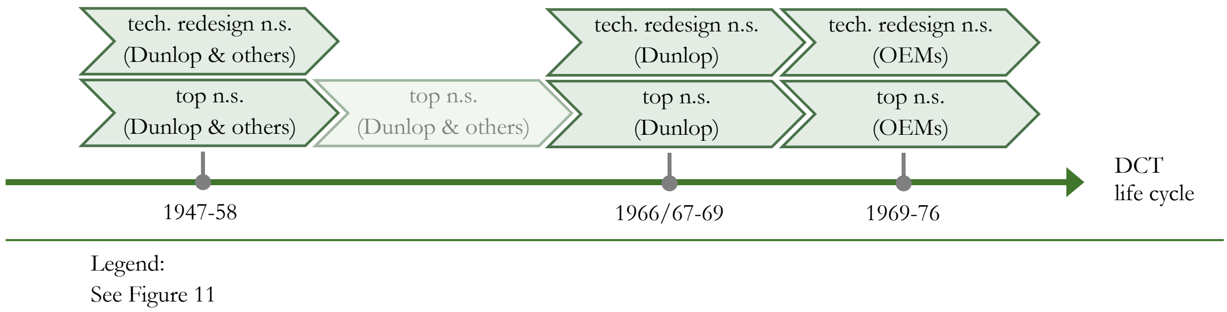
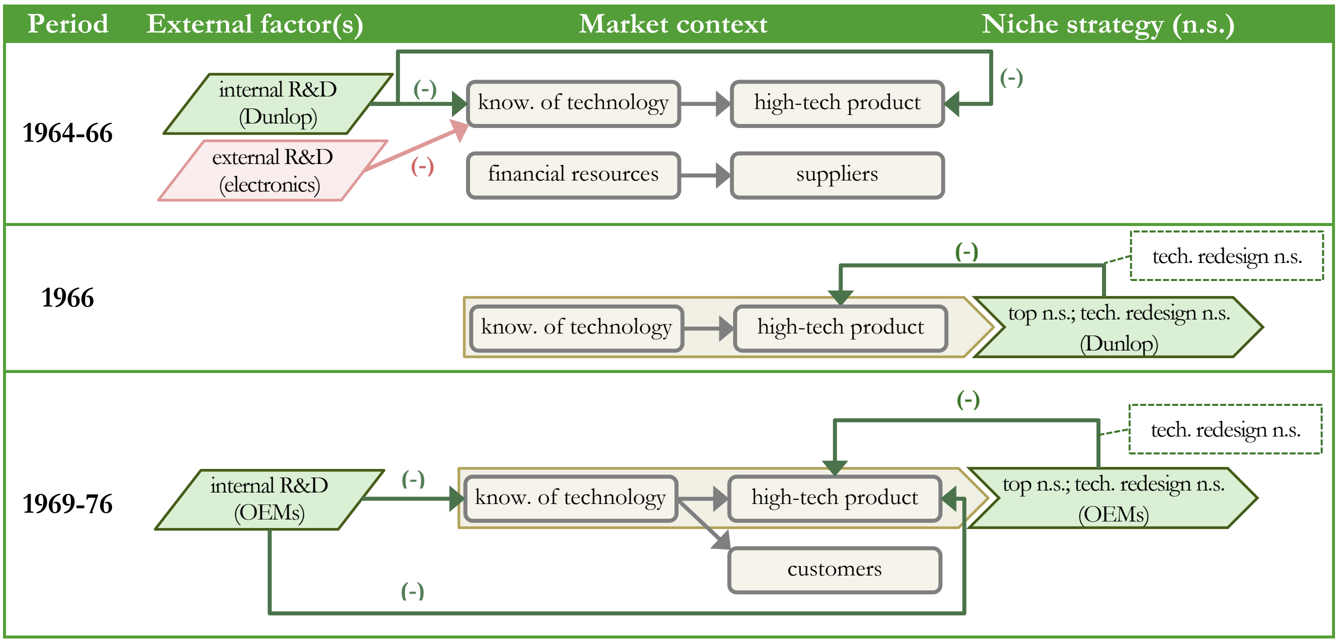


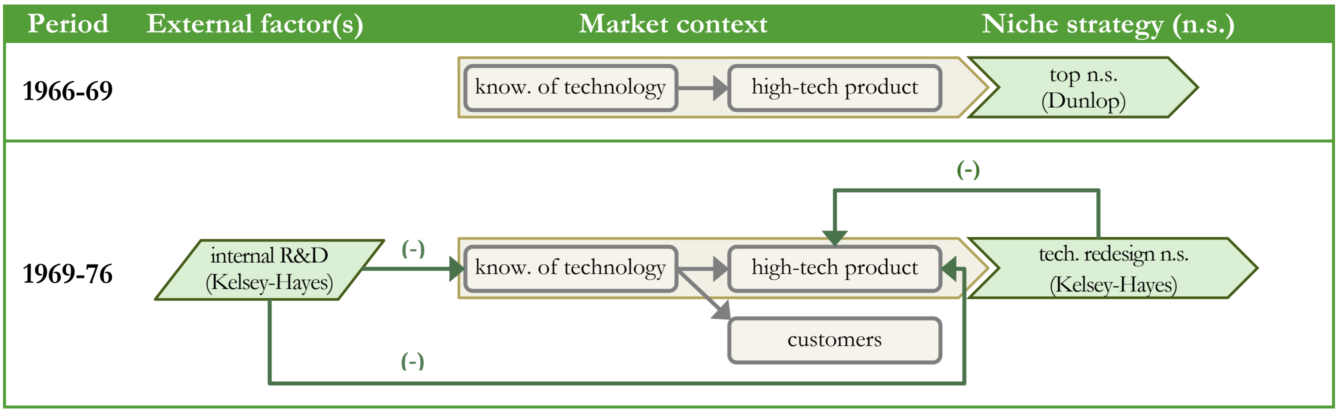
Figure 33: Chronology of niche strategies – ABS technology

5.B From a market perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.

From a market perspective, the logic for the sequence throughout the entire market adaptation phase resembles to simultaneous incremental efforts being made by automakers and OEMs in order to: (1) reduce the complexity of the technology and its price by 'technological redesign' niche strategy on one hand; and (2) target a sufficiently affluent and willing-to-pay-for-adoption customer segment via the 'top' niche strategy, on the other hand.



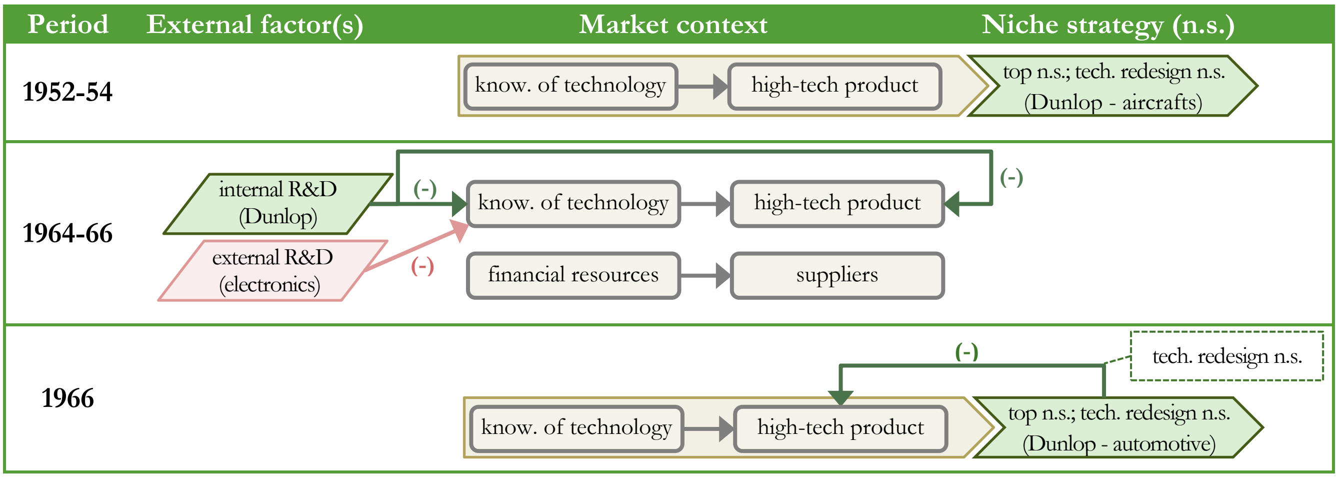
Equally so, we may observe that between 1966 and 1976, the logic of the sequence of niche strategies could be based on the –emergent– competitive response of vehicle manufacturers to new product introductions. For instance, "[s]hortly after the Jensen's introduction, Ford Motor Co. started a hard drive toward antiskid. […and] staged an informal antiskid competition asking all interested suppliers to demonstrate their hardware" (Cutter 1968, p.206). For this particular situation, the observed sequence was 'top' niche strategy, followed by 'technological redesign'. Vehicle manufacturers can respond to competitors' product introduction and regain the lost ground by developing a simpler technological offering which can still satisfy customers' needs.



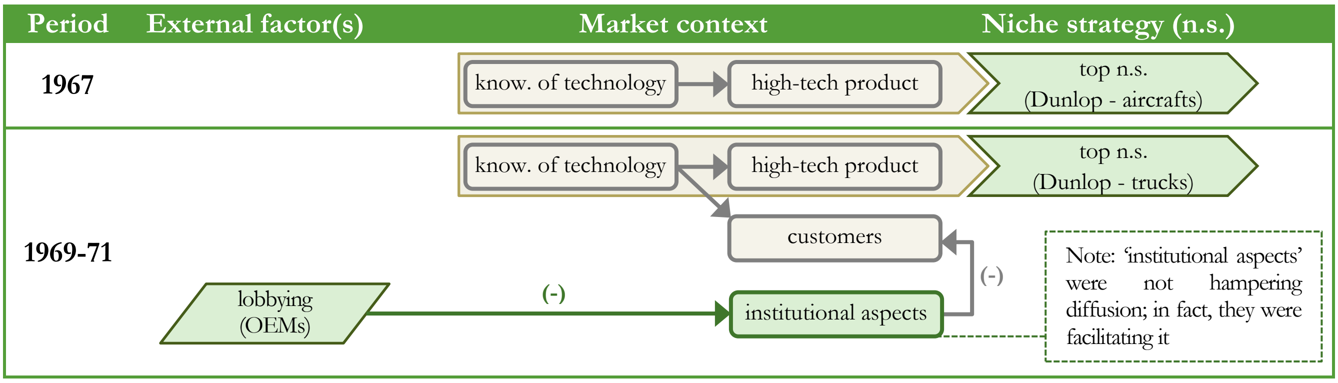
5.C From a company (incl. network of companies) perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.

For Kelsey-Hayes, GM and Bendix the minimum requirement of at least two subsequent niche strategies is not met, and therefore it makes no sense in discussing about a sequence; neither for Bosch, since the company introduced the product directly via a large-scale market strategy.

Dunlop, on the other hand, leveraged its know-how from aviation, and expanded into adjacent market segments: luxury cars and heavy trucks. Without segmenting to a particular time period, the overall logic can be seen as emergent, since there is no indication that Dunlop used the initial market introduction in aviation as an up-front, planned stepping stone before expanding to automotive.



However, if we are only to look only at time period after the introduction of electronic ABS by Dunlop, the case can be interpreted as a potentially deliberate sequence of niche strategies. Simultaneously, the company was active in the market for aircrafts and heavy trucks. It had entered the latter as an adjacent customer segment around 1966. In 1967, Dunlop introduced an electronic version of the Maxaret system on aircrafts, and around the same period –or 18 months prior to October 1969– it began operational testing of their Maxaret MkIIE on 100 tractive units (see Commercial Motor 1969). "Full-scale production will not start until the results of these operational trials have been declared satisfactory" (Commercial Motor 1968, p.52), which eventually did happen since in 1969 sales already started; arguably Dunlop commanded a lower price point than in aircrafts. The last evidence comes from the fact that Dunlop did not attempt to introduce an electronic ABS unit for cars, which had proven unsuccessful in the earlier case, i.e. the Jensen FF. Thus, on the basis of the above, Dunlop is very likely to have used a deliberate succession of 'top' niche strategies: first for electronic ABS in aircrafts, and thereafter in heavy trucks. This sequence had been formerly tried and tested on the mechanical version of ABS, with the exception of the 'technological redesign' niche strategy not being commanded anymore.



There are two interesting observations to be made with regard to the sequences used by Dunlop. Firstly, the reader is advised to note that it did not materialize completely in the automotive industry, but rather transitioned from aircrafts to heavy trucks. Secondly, OEMs were making use of the external factor 'lobbying' in the U.S. to accelerate diffusion by making ABS mandatory on heavy trucks.

5.D Why did a sequence of niche strategies – if any – emerge during the market adaptation phase?

The reasons for the emergence of the sequences of niche strategies are better explored if segmented according to type of logic: emergent or deliberate.

For the emergent logic, the reasons were largely of three kinds: (1) diminish magnitude of barrier, (2) search of customer segments, and (3) competitive response. For the first rationale, the reader is advised to refer to recently explained market-level-wise incremental efforts to reduce technological complexity and decrease price. For the second rationale, one must look no further than the shift from aircrafts to automotive, when Dunlop expanded to adjacent customer segments by deploying 'top' niche strategy coupled with 'technological redesign' in two subsequent instances: around 1952 in aviation, and then in 1966 with the Jensen FF. The third rationale, i.e. competitive response, can be illustrated by the sequence 'top' niche strategy –by Jensen and Dunlop– followed by 'technological redesign' –by Ford and Kelsey-Hayes. The large U.S.-based vehicle manufacturer decided to experiment with ABS systems shortly after the Jensen's introduction.

One might argue that product differentiation was another reason. The first instance when it might be tempting to do so would be when the electronic ABS units of the early 1970s were rivalled against their former mechanical counterparts. This would be erroneous, since specifically in the automotive industry, the ABS product introductions were always competing with other state of the art technologies, rather than with the old products: the early mechanical units were almost phased out by the time the new electronic units came to market; the same for heavy trucks. In this sense, the product differentiation was among niche strategies occurring at more or less the same moment in time, and not between older instances.

The second situation when it might be even more tempting to say that product differentiation rests at the basis for the emergence of the sequence is when Bendix made use of the 'top' niche strategy a couple of years after the introductions by Kelsey-Hayes or GM via 'technological redesign'. The former was an all-wheel system, yet more expensive; while the latter was only a rear-wheel system, but nevertheless cheaper due to the decreased technological complexity. The main argument why it would be false to assume so is temporality. According to the theory laid out in section 3.3.2 these niche strategies cannot be regarded to have taken place one after the other, despite the two-year time period that separated them. Perhaps, this theoretical restriction could be criticized had

Bendix started work on the four-wheel system after the market introduction by Kelsey-Hayes or GM. However, case evidence suggests that all OEMs were developing their products at more or less the same time; merely with different value propositions in mind: "Kelsey's engineers feel it's most important to move into this field slowly with a simple, low-priced system that will prevent rear-end slewing. […] By contrast, Bendix thinks that the front-end antiskid should be included in the system" (Cutter 1968, p.206).

As far as the deliberate sequence by Dunlop is concerned, this was arguably made possible due the great similarities between mechanical and electronic ABS in terms of functionality, value proposition, etc. The central actor could essentially duplicate part of the former emergent sequence. The underlying rationale for the emergence of the sequence would be market skimming.

5.E Based on which criteria did companies opt for a wait-and-see, niche or large-scale introduction strategy?

Bosch –and its collaborators– used a wait-and-see strategy as described in section 5.2.3. The company had a trial version available from 1970 (Daimler Communications 2008); "[s]eries introduction was to follow as soon as possible, but the reliability of the control electronics still left much to be desired" (Robert Bosch GmbH 2003b, p.32). Bosch waited for eight years and continued to develop the product until no barrier to large-scale diffusion was present. That is not to say that during this time Dunlop and its collaborators worked in secrecy: "Daimler-Benz introduced this first generation of an anti-lock braking system for cars, trucks and buses to the public on the test track in Untertürkheim on December 12, 1970 – with a resounding echo by an enthusiastic expert world and press. The principle had been found to be convincing" (Daimler Communications 2008).

5.2.6.CONCLUSION

6.A How do the case results contribute towards answering the research questions?

Table IX summarizes the case results which contribute towards answering the six research questions. Conclusions from earlier sections constitute the basis for the information presented in the right hand-side column.

Table IX: Preliminary answer to research questions based on the ABS case results

Research question	Preliminary answer
1.What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?	Once again, the methodology proposed under section 4.4 proved well-suited for the investigation of sequences of niche strategies.
2.How do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	The core factor 'new high-tech product' hampered diffusion throughout the entire span of the market adaptation phase. Contrarily, the 'suppliers' barrier remained active for a significantly shorter period of time. The social barrier of 'customers' and the technological barrier 'new high-tech product' were the last to disappear.
3.Why do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	The change in the barriers can be explained by three main aspects: (1) external factors; (2) niche strategies may provoke the creation of new barriers to large-scale diffusion; and (3) the change from one market to another –for e.g. from aviation to automotive– influences the strategic analysis of the market context, which in turn impacts how the barriers are interpreted.
4.Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?	Bosch –as the central actor– used a wait-and-see niche strategy. The company had already an early working version of the product when other manufacturers –for e.g. Kelsey-Hayes, Bendix– started introducing the technology to the market. However, Bosch continued to develop the product internally up until the moment when no barrier to large-scale diffusion was present. Furthermore,

	barriers could be mitigated without necessarily introducing the technology: demonstrations to the media, external factors. Large-scale introduction strategy was yet again used when no more factors were found to hamper diffusion.
5.What could be the logic and rationale behind sequences of niche strategies for market creation?	For emergent logic, the reasons were divided in three categories: (1) diminish magnitude of barrier, (2) search of customer segments, and (3) competitive response. Dunlop, on the other hand, made use of a deliberate sequence of 'top' niche strategies to exploit the market potential of the technology in subsequent customer segments: aircrafts, followed by heavy trucks. The rationale can be summarized as (4) market skimming.
6.What are logical sequences of niche strategies in the selected industry?	For secondary components –such as ABS– in the automotive industry, the sequence of the two simultaneous niche strategies –'technological redesign' and 'top'– would prove useful in helping OEMs and automakers to lower the complexity and costs of such components, i.e. 'new-high tech product' barrier. Secondly, 'top' niche strategy can be followed by 'technological redesign' as a competitive response of vehicle manufacturers to the former. Alternatively, 'top' followed by 'top' can be used for deliberate market skimming efforts. Please note that the succession of niche strategies employed by Dunlop –as explained under section 5.2.5– entailed expanding from another industry/market to automotive.

The ABS case offered interesting insights towards answering the research questions.

6.B What are the theoretical implications of the case results?

Similarly to the DCT case, the conceptual model is yet again supported; this time, except for one influence: niche strategies proving effective in completely removing barriers. They merely helped decrease the magnitude of the core and contextual factor, or create completely new barriers in some instances.

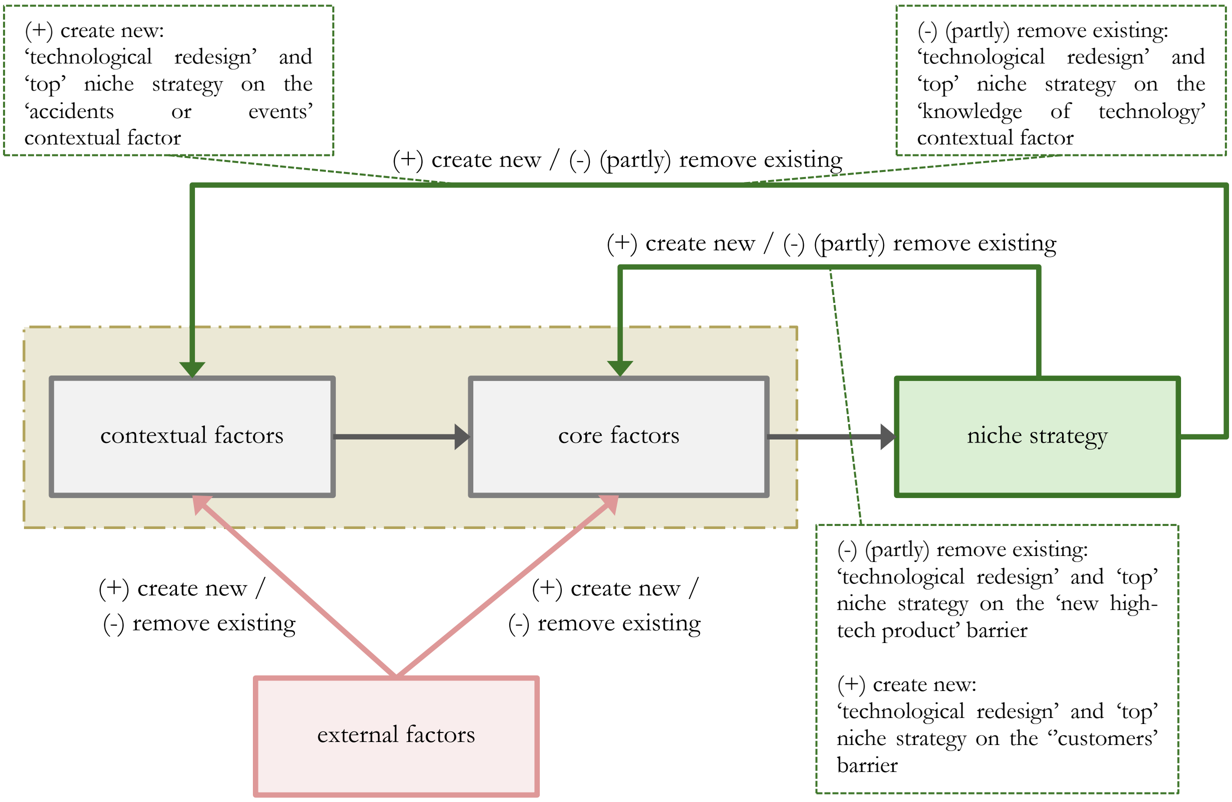


Figure 34: Conceptual model – ABS technology

The case offered five interesting reflection points. Firstly, a previously undefined contextual factor was uncovered: financial resources; which was not featured in the model by Ortt et al. (2013). Thus, either a new contextual factor is added or an existing –fairly similar one– is expanded. Since, the factor might also be encountered in the PEMFCV case, recommendations in this regard will be made in a later chapter.

Secondly, in section 3.1.2 it was mentioned that niche strategies would not include the aspect of differentiation from competitors. While this appears to remain generally true for most instances, there is an example that shows how niche strategies can be used to differentiate between product offerings, and even between themselves. In the late 1960s, Kelsey-Hayes and GM opted for a simpler less-expensive version via technological redesign, whereas Bendix chose to offer a more technologically advanced system –at almost double the cost due to the increased complexity– which it introduced via the top niche strategy. For this situation, one may note how niche strategies were used to differentiate the product introductions from one another.

Thirdly, the explanation of the 'technological redesign' niche strategy requires adjustment. As observed in the early strategic niche in aircrafts, the product was not necessarily introduced in a simpler –and therefore cheaper– version, but rather in a technological configuration which could be produced within the existing knowledge.

Fourthly, the same niche strategy, but not in between 1969 and up to 1976, elicits characteristics of a geographic niche strategy. The introduction of the technology in its simpler variant made sense in countries where the reduction in yaw proved more important than the aspect of steerability under braking. The typical luxury cars in the U.S. fit the description, whereas these systems were "not highly regarded by the majority of the European observers because they give little to no reduction in stopping distance and cannot prevent the ability to steer from being lost when the front wheels lock-up" (Curtis 1971, p.360).

Lastly, it is interesting to note that the market stabilization occurred primarily in the market segment of luxury cars. Intuitively this seems a bit odd. However, there is one factor from the literature which can explain how this was possible. Veloso and Fixson (2001, p.250) argue that "the modular characteristics of both conventional and ABS braking systems played a crucial role in giving a clear up-front perception of the potential ABS market, and enabled development and testing somehow independent of the assembler." Since the 1970s, suppliers of ABS could spread their investment costs over multiple vehicle manufacturers, "provided that they were able to meet the necessary reliability and safety concerns of the automaker" (p.250).

6.C What are the managerial implications of the case results?

The modularity of the technology can help OEMs diffuse a secondary technology to a large-scale using what would be typically considered a niche. The example of the mass market adoption of ABS in the customer segment of luxury cars proves this point.

Secondly, the deliberate sequence employed by Dunlop in the form of 'top' followed by 'top' niche strategy need not be limited to the shift from another industry to that of automotive. In fact, it could be imagined how managers could subsequently skim the market by employing the same exact sequence.

Lastly, this case really illustrates the usefulness of a wait-and-see strategy. In some situations extended product development in absence of market introduction, monitoring of the market context, and even influencing it via external factors can outperform first-to-market competitors.

5.3. CASE 3: PROTON EXCHANGE MEMBRANE FUEL CELL VEHICLE (PEMFCV)

Before proceeding to the actual case report, there are some observations to be mentioned. This particular case presents some key differences as compared to the previous two cases. In the current paragraph these key differences will be listed shortly, and in the remainder of the sub-section they will be explained at more length. Firstly, the focus will be on only one specific fuel cell technology –proton exchange membrane fuel cell– whereas the other technologies –DCT and ABS– were investigated without segmenting to a specific type. Secondly, while for DCT and ABS the case report was quite specific in describing the technological niches occurring during the market adaptation phase, this case will be briefer in this respect; some comments will be made with respect to experimental projects, with the primary scope of depicting the status of the barriers. Thirdly, this last case is more peculiar given that the large-scale diffusion hallmark has not occurred yet, i.e. the technology has yet to diffuse in a large-scale market.

Fuel cells come in a variety of sizes, power output, and types (Fuel Cell Today 2012d). The main characteristic on the basis of which fuel cells are classified is the nature of the electrolyte used in the cell (Behling 2013a; Fuel Cell Today 2012d), which "can be aqueous, solid, or molten; alkaline, neutral, or acid; or polymer, chemical substance, or ceramic" (Behling 2013a, p.12). The case study research yielded six types of fuel cells: proton exchange membrane fuel cells (PEMFCs) or polymer electrolyte fuel cells (PEFCs); direct methanol fuel cells (DMFCs); alkaline fuel cells (AFCs); phosphoric acid fuel cells (PAFCs); molten carbonate fuel cells (MCFCs); and lastly solid oxide fuel cells (SOFCs) (Behling 2013a). In fact, DMFC is a sub-type of PEMFC, since it uses a polymer membrane as the electrolyte (Behling 2013a), with the added advantage of it being "able to draw the hydrogen from liquid methanol [in fact a diluted methanol solution (Marscheider-Weidemann et al. 2009)], eliminating the need for a fuel reformer. Therefore pure methanol can be used as fuel, hence the name" (Fuel Cell Today 2012a). If DMFC vehicles are to be found, they will be considered in the investigation, since they are included in the PEMFC technology family.

The type of electrolyte determines the operating temperature range, which has an impact on the materials required in the fuel cell and also on the type of fuel to be used –i.e. pure hydrogen, hydrogen with impurities, methane, methanol, etc. (Behling 2013a). This entails that different types of fuel cells are suitable for different kinds of applications (Fuel Cell Today 2012d). "PEMFCs are regarded as best suited for fuel cell vehicles (FCVs) and small stationary applications. They have been the fuel cells most favoured by researchers and developers. […] Over the decade, PEMFCs for FCVs and small stationary applications received much attention and investments that likely surpass all the other types of fuel cells combined. More corporations and research institutions are involved in R&D of PEMFCs than in any other fuel cell type" (Behling 2013a, pp.13, 15). Furthermore, "PEMFC cells are currently the leading technology for light duty vehicles and materials handling vehicles" (Fuel Cell Today 2012c), which entails that narrowing the scope down to PEMFC will not elude any key developments in the status of the barriers to large-scale diffusion, or in the succession of niche strategies, in the field of automotive.

Secondly, it is relevant to make one important distinction between the current research work and earlier publications. The focus of this thesis is on strategic niches, whereas a significant part of the literature investigated had researched technological niches (see Behling 2013b) or innovation systems (see Ball et al. 2009). In that situation other theoretical frameworks would be more appropriate; such as Strategic Niche Management or Functions of Innovations Systems. Throughout this case report technological niches will not be comprehensively investigate; nevertheless they are steering with respect to unravelling the magnitude of the barriers to large-scale diffusion at a particular moment in time. Therefore, where appropriate, the status of the core and contextual factors will be investigated by relating to experiments and demonstration projects that pertain to technological niches.

Thirdly, as opposed to the previous two cases, this one is more peculiar in the sense that the large-scale diffusion hallmark has yet to materialize. The technology development and market commercialisation strategies during the market adaptation phase are still on-going.

On a last note, as opposed to the other cases, the topic of PEMFC vehicles has been comprehensively documented by the scientific literature. For instance, the work by Behling (2013b) on this topic contains over 700 references alone. Thus, it may appear that only selected references will be prevalently cited –(Behling 2013b), (Ball et al. 2009), etc.– but each of these sources contain a wealth of specific descriptive facts and citations with regard to the case topic.

5.3.1.INTRODUCTION

1.A Define the radically new high-tech product, i.e. the functionality it provides, the technological principle(s) on the basis of which it operates, and the main components of the system / first tier of sub-systems.

PEMFCVs are defined as any vehicle which employs a PEMFC (including DMFC) to power an on-board electric motor used for propulsion. This definition explicitly excludes the use of fuel cells in auxiliary power units, whereby "another engine is used for propulsion, but the fuel cell is used to run part of or the entire vehicle electrical system" (Barbir 2013, pp.375–376). The most common form is that of a hybrid which has had its internal combustion engine replaced by the fuel cell; it provides a continuous source of energy. A secondary battery is used for regenerative braking (Dell et al. 2014).

The fuel cell itself generates electricity by an electrochemical reaction of two reactants: the fuel and the oxidant; hydrogen being most commonly used as the fuel, and oxygen as the oxidant. PEMFC generate electricity by using positive hydrogen ions as carrier ions from the anode to the cathode side. (Behling 2013a)

The main components of the PEMFCV are: the PEMFC stack providing the energy, the fuel storage unit – typically employing pressurized hydrogen– and the electric motor (adapted from Dell et al. 2014); and optionally a battery.1.B Identify and describe the invention hallmark.

The radical technology at the basis of the PEMFCV is essentially the fuel cell. The principle behind its operation was demonstrated in 1801 by Humphry Davy (Fuel Cell Today 2012b), but the discovery of the technology is generally attributed to Sir William Grove, who in 1839 "designed the first working fuel cell" (Mytelka & Boyle, 2008) (Schaeffer 1998) . Interestingly, Grove's publication actually "came out a month later than that of Professor Christian Friedrich Schoenbein in the January issue of the Philosophical Magazine in 1839 that for the first time described an experiment, and showed the fuel cell effect." (Sandstede et al. 2010, p.156). The term fuel cell was used for the first time half a century later –in 1889– by Charles Langer and Ludwig Mond (Fuel Cell Today 2012b). But, "[a]round the turn of the century, the dynamo generator (1866, Siemens), combustion engines (1876 Otto; 1897, Diesel) and the gas turbine (1900, Stolze) were successfully introduced to the market, so there was little interest on the part of industry in the development of an electrochemical generator. More intensive work on the basic principles of fuel cells was only begun around 1950 in England, then Germany and the USA." (Marscheider-Weidemann et al. 2009, pp.348–349)

In terms of the development efforts targeted at PEMFCs, GE can be seen as the central actor throughout 1954-1983. Willard T. Grubb and Leonard Niedrach –researchers at General Electric (GE)– "invented the first PEMFC in June 1955" (Behling 2013b, p.425). The research on the 'ion-exchange membrane cell' had started just a year earlier, in 1954 (Behling 2013b). In 1958 "Niedrach devised a way of depositing platinum onto the fuel cell, which accelerated electrochemical reactions and resulted in a significantly higher efficiency" (Behling 2013b, p.425). The device resulting from the combined efforts of the two GE researchers was initially referred to as the 'Grubb-

Niedrach fuel cell' (Behling 2013b), but GE opted for the trademark name 'solid polymer electrolyte (SPE)' (Sandstede et al. 2010).

Another key development took place in 1968, when Du Pont developed Nafion –"an advanced membrane […] which had excellent thermal, chemical, oxidative, and mechanical stability, and seemed perfect for fuel cells" (Behling 2013b, p.426)– which GE quickly adopted for its PEMFC systems in 1969.

Applications targeted by GE during the 1960s were related to NASA's twelve Gemini missions in space. The Gemini missions were the stepping stone for space manned missions, and ultimately for the Apollo lunar programme. In 1963, GE manufactured the first prototype for NASA, which consisted of two 1kW modules responsible for providing the primary power supply –not propulsion, therefore not PEMFCV– for the Gemini space vehicles (Behling 2013b). The first four of the Gemini missions "flew with batteries instead of fuel cells. GE redesigned their cells, and the new cells, despite malfunctions and poor performance on Gemini 5 [in 1965 (Maeda 2003)], adequately served for the remaining Gemini missions" (Behling 2013b, p.426).

By 1968, NASA had already decided to use the AFC technology for the Apollo programme. "There had been a perception within NASA that the polymer electrolyte was intrinsically resistive and that the requirement for a higher power density fuel cell system for Apollo could be better met by the alkaline fuel cell. This, for all practical purposes, put the SPFC [i.e. PEMFC] on the shelf for space applications for the next 20 years" (Prater 1990, p.239).

Despite the setback GE continued work on the PEMFC technology, and the company is said to have invested "$8.5 million of its own money over the 1960s and 1970s" (Behling 2013b, p.426). In 1969, GE used the new Nafion membrane in a second generation PEMFC system. This was "a 350 W module that flew in three Biosatellite spacecraft (1966-1969), which NASA built to assess the effects of spaceflight on living organisms" (p.427), and later "a 3 kW flight-qualified module for a Navy high-altitude Balloon program" (p.426). By the mid-1970s, GE had redirected their efforts into PEM water electrolysis for the U.S. Navy (Behling 2013b).

The year of 1984 marks the date when GE made the strategic decision to exit the fuel cell business. Consequently, it licensed the technology know-how to Siemens AG in Germany, and during the mid-1980 the company "transferred PEMFC and electrolysis technology to UTC-Hamilton Standard" (Behling 2013b, p.426).

In 1984, Ballard Research was commissioned and funded by the Ottawa's Department of National Defense (DND) "to produce a low-cost PEM fuel cell that could run on impure hydrogen produced by reforming a liquid fuel like methanol […] Over the next several years, Ballard developed ever more powerful and smaller PEMFC stacks, establishing itself as the world leader in PEMFC technology (Behling 2013b, p.427). Throughout the early 1980s a series of demonstration and experimental projects followed, but there was no actual market introduction.

5.3.2.CHRONOLOGY OF STRATEGIC NICHES

2.A Identify and describe the first market introduction of the technology, and the hallmark of large-scale diffusion.

Between the invention of the PEMFC in 1955 and the first market introduction of the PEMFCV in the late 1980s there were several FCV demonstrations, but the technical configuration used a competing fuel cell technology: AFC.

Based on the case research, the first documented FCV application was in August 1959, when an alkaline fuel cell developed by Francis Bacon had been used "to power a fork lift truck and for welding. A month later, […] the US company Allis-Chalmers […] demonstrated a 15 kW fuel cell stack that consisted of 1008 [alkaline fuel] cells and was used to drive a tractor [(Sandstede et al. 2010)]" (Schaeffer 1998, p.358). Later, in 1967, General Motors demonstrated its Electrovan "based on alkaline fuel cells and fuel storage in the form of cryogenic hydrogen and oxygen" (Eberle et al. 2012, p.8780). Other applications of the AFC technology in vehicles followed. "In 1965, Siemens equipped a boat with a 500W [alkaline] fuel cell […] Later they built 6 kW units […] for the propulsion of a submarine" (Sandstede et al. 2010, p.184); VARTA equipped a forklift in 1966 with a 1.5kW alkaline fuel cell (Sandstede et al. 2010).

The first documented PEMFCV application occurred decades later. This moment also corresponds to the first market introduction hallmark, i.e. sometime between 1984 and 1989. Siemens had experimented with AFC technology for the propulsion of boats and submarines, but after licensing the PEMFC technology in 1984 from GE "from then on used [it] for submarines of the German Navy, quite a number of which had already been built" (Sandstede et al. 2010, p.185). Around the year 1987, the U.K. Royal Navy received a Ballard fuel cell for evaluation (Prater 1990); and "adopted this technology […] for its submarine fleet" (Behling 2013b, p.426). Having received an identical unit in 1987, the U.S. firm Perry Energy System employed an updated version of the technology for a two-man observation submersible in 1989 (Prater 1990; Behling 2013b). The time interval 1984-1989 will be considered as the first market introduction hallmark.

December 2000 marks the date when "Ballard's first […] manufacturing plant for large-scale production of portable and automotive fuel cells was opened in Burnaby, British Columbia" (Behling 2013b, p.427). However, up to this day, the large-scale diffusion hallmark has yet to materialize.

2.B Present chronologically the different niche applications of the technology.

SUBMARINES

As depicted in the previous sub-section, the British Navy adopted the PEMFC technology for its submarine fleet in the 1980s. Siemens, using the technology developed by GE, equipped submarines of the Germany Navy. The first commercial fuel-cell powered submersible was released by Perry Energy Systems in 1989, using Ballard's PEMFC technology (Barbir 2013).

Also in the 1980s, the U.S. Navy is said to have "commissioned studies into the use of fuel cells in submarines where highly efficient, zero-emission, near-silent running offered considerable operational advantages" (Fuel Cell Today 2012b), but the data is not specific enough regarding the type of fuel cell technology used.

More recently, in 2011, the German and Italian Navy were reported to be using Siemens-built PEMFC units to power submarines, as part of their fleets (Pleitgen 2011; Naval Technology 2011).

AUTOMOTIVE

Regarding the field of automotive, PEMFCVs were introduced both in public transport buses and passenger vehicles.

BUSES

"In 1990, Canada's Federal Department of Energy Mines and Resources, the Canadian Province of British Columbia, and the Federal Department of Energy Mines and Resources implemented a government-industry cost-share program to develop a PEMFC-powered bus. […] The bus was to seat 20 passengers" (Behling 2013b, p.428). The company chosen as the prime contractor was Ballard, which "[i]n 1993 […] introduced the world's first PEMFC bus built by New Flyer, which drove on the streets of Vancouver […] The 32 ft, low-floor transit bus, P1, was powered by 90 kW Ballard stacks" (Behling 2013b, p.428). Only two years later, Ballard introduced the P2. This second generation bus was also based on a New Flyer Model –40 IF bus– and featured a 205kW PEMFC stack, with a range of up to 250 miles (Behling 2013b).

Nowadays, "[t]he global bus industry is smaller than the passenger car industry and has fewer players. There have been about a dozen or more fuel cell bus manufacturers and about 10 fuel cell stack developers. Those currently [i.e. 2013] producing PEMFCs for buses likely include Ballard, COPPE UFRJ, Hydrogenics, Hyundai, Nedstack, Nuvera, Proton Motor, Toyota, Tsinghua University, and UTC." (Behling 2013b, p.525)

PASSENGER VEHICLES

Starting with 1994, when Daimler-Benz presented the first experimental PEMFC passenger vehicle, the NECAR 1, there were other similar pilot projects: Daimler-Benz again in May 1996, Toyota only five months later in October of the same year, Mazda in 1997, etc. For a comprehensive list of the experimental projects interested readers are directed to the work by Behling (2013b). For the scope of this research, suffice it to say that by the early 2000s, "virtually every major automaker entered the fuel cell race" (Behling 2013b, p.430) (Fuel Cell Today 2012b).

The first commercialization of a passenger vehicle using a PEMFC stack occurred in December 2002, when "Toyota begins limited marketing of the TOYOTA FCHV […] Two TOYOTA FCHVs are leased in the U.S. and four in Japan" (Toyota Motors 2004, p.2010). In 2008, Honda also began leasing the FCX Clarity PEMFCV (Fuel Cell Today 2012b).

MATERIALS HANDLING VEHICLES

The product applications in the customer segment of materials handling vehicles tend to be indoors –e.g. warehouses– where the amount of emissions needs to be controlled (Behling 2013b). "[C]ompared to the traditional material-handling equipment, which generally use propane and diesel internal combustion engines (ICE) or leadeacid batteries [f]uel cell material handling vehicles operate silently, […] and offer faster refueling ["forklifts take only one to two minutes to refuel, compared to the half hour or longer it takes to change out a battery" (FuelCells.org 2012)] as well as significantly longer run times compared to their conventional counterparts [12-14 hours as compared to 6 hours for battery-powered forklifts (FuelCells.org 2012)]. [They] also do not require lengthy recharging time or need large amounts of plant space for recharging equipment, as compared to battery-powered vehicles" (Behling 2013b, p.530).

The first four PEMFC forklifts were deployed at a warehouse in Tennessee, U.S.A, back in 2004. "Since then, fuel cell-powered material handling vehicles have become increasingly popular at warehouses, distribution centers, and factory floors in the United States and Canada." (Behling 2013b, p.530) In fact, in the area of transportation it is in this product application where the greatest commercial activity occurred (Fuel Cell Today 2012b). For instance, by July 2011, a total of 2220 forklifts were estimated to have been deployed in North America; units sold had been generally insignificant until 2008 (Behling 2013b). And as recently as 2015, a total of 7724 units –which represent both deployed forklifts and additional fuel cell stacks purchased in advance for replacement purposes– were estimated for North America (FuelCells.org 2015).

OTHER

"Some transportation applications, such as aircraft, locomotives, trucks, mining vehicles, cranes, marine vessels, golf carts, bikes, scooters, and water taxis, are still in an early stage of development" (Behling 2013b, p.511). For a comprehensive list of speciality vehicles please refer to the list compiled by FuelCells.org (2015).

SUMMARY

2.C Depict visually the different niche applications, starting with the first market introduction and concluding with the large-scale diffusion.

The niche applications of the PEMFCV technology were as follows: submersibles, automotive –public transport buses, passenger vehicles– and lastly materials handing vehicles (forklifts). Figure 35 presents this schematically.

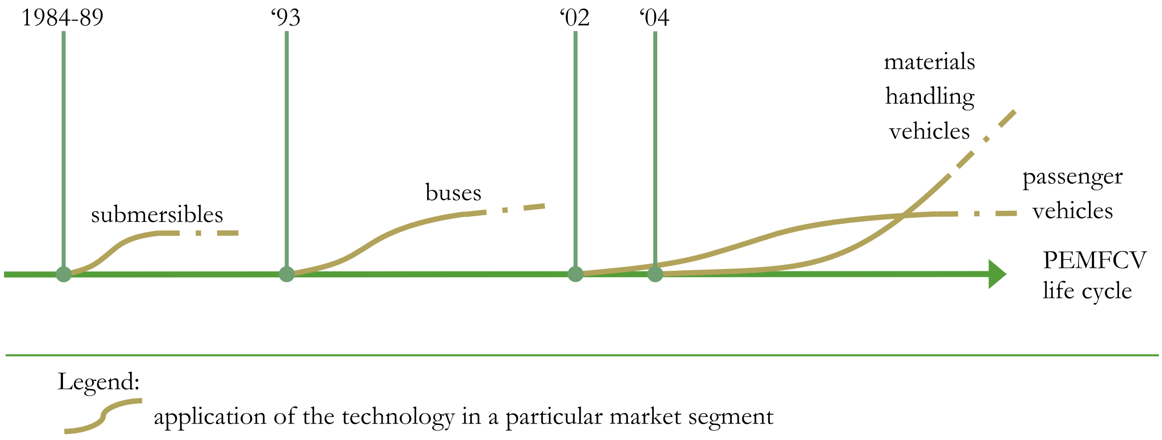


Figure 35: Graphic depiction of applications of the PEMFCV technology in particular market segments

For the visual representation of the complete pattern of development and diffusion, interested readers are directed to Appendix 3: Patterns of development and diffusion.

5.3.3.CHRONOLOGY OF NICHE STRATEGIES

Similar to the previous two cases, before proceeding to the analysis of the barriers which were found to hamper large-scale diffusion, it is worthwhile to reflect on those barriers which did not do so. In the case of the PEMFCV, the core factor of 'suppliers' was absent. Ballard played a key role in the supply of PEMFC units during the early stages of the market adaptation phase. It had established itself as the industry leader in this respect by the end of the 1980s (Behling 2013b). Later on, other OEM of fuel cells stacks emerged (see Behling 2013b).

EARLY 1980S

In 1983, the Government of Canada "decided to have a Canadian firm [Ballard] improve the cost and performance of PEMFC technology" (Behling 2013b, p.427). This would entail that, at that time, the price/performance ratio was not satisfactory, which was caused by –at least– the following contextual factors. Firstly, the knowledge of the technology was still lacking, which would explain why the Government of Canada had commissioned Ballard to perform an evaluation of the potential of the PEMFC technology in the first place. Secondly, one of the main reasons for the high costs is that this type of fuel cell requires platinum –an expensive natural resource– which functions as a catalyst at the anode and cathode side (Carlson et al. 2005). In fact, Prater (1990) assigned the high cost of the membrane and that of the platinum loading –as compared to the competing PAFC technology at the time– as one of the decision drivers behind GE's withdrawal from a potential commercial market for PEMFC in in the early 1980s.

Except for industrial use of hydrogen, there was no infrastructure available which would cater to a mass market for PEMFCVs (see FuelCells.org 2015; section "Worldwide Hydrogen Fueling Stations"). Building up such an infrastructure would require significant amounts of financial resources, as illustrated in Figure 36 by the corresponding contextual factor. The factor remained prevalent well into the late 2000s (see Ishitani 2010).

In terms of natural resources, hydrogen can be reformed from commodity products such as methane. With the exception of volatility of variable costs due to spikes in the market price of raw materials, the contextual factor of 'natural resources & labour' would not have influenced the core factor of 'complementary products & services'.

The technology was still advancing at the time, and there had been no clear technological winner with respect to the fuel required by the PEMFCVs: methanol, methane, liquid/gaseous hydrogen, etc. However, it would be wrong to conclude that the contextual factor 'knowledge of technology' had influenced the availability of complementary products. That is because if we are to take the literal definition from the paper by Ortt et al. (2013, p.4), the technological know-how "required to produce, develop, replicate and control the technological principles in [the] product" was sufficient; rather the market had yet to decide which technological configuration was required from the associated hydrogen infrastructure.

This latter point hints at a contextual factor not listed by Ortt et al. (2013): installed base. The concept is well known in the literature on the topic of network externalities (see Katz & Shapiro 1985; Katz & Shapiro 1986), and it will be detailed upon under section 5.3.6. For the time being, suffice it to say that it refers to the number of FCVs –or other hydrogen-running road-certified vehicles– in operation, which would require refuelling from hydrogen stations on a reoccurring basis. Put simply, "[t]here is resistance to up-front preparation of FCV hydrogen infrastructure, since there are no vehicles around yet are no vehicles around yet" (Ishitani 2010, p.14).

During the early 1980s there were also no readily available large-scale production facilities. In fact, this core factor would persist at least until December 2000, when Ballard opened the first manufacturing plant for PEMFC stacks (Behling 2013b).

As late as 2009 there were no internationally-harmonized standards, codes and regulations with respect to the deployment of fuel cell technology on public roads. For the same year, "surveys generally show[ed] that there is a great acceptance, but a low knowledge level for hydrogen technologies. Males and people with a higher education level seem to have a greater acceptance. There is practically no opposition to the introduction of hydrogen as a fuel" (Ball et al. 2009, p.266).

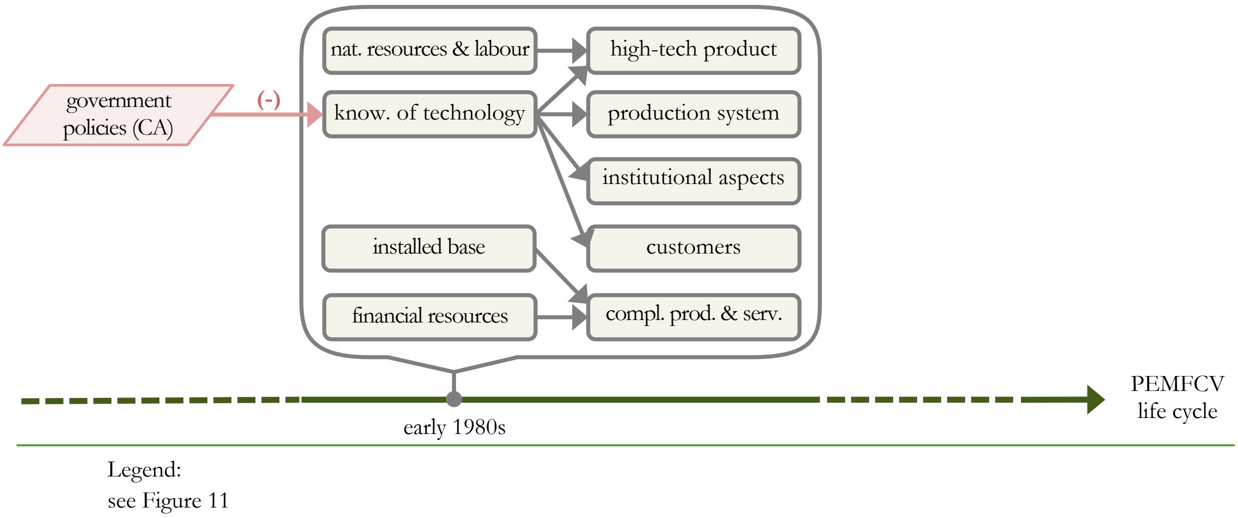


Figure 36: Market context of the PEMFCV technology in the early 1980s

The external factor 'government policies' refers to the Canadian (CA) government's initiative to sponsor Ballard in advancing the knowledge of the technology.

1984-1989

When PEMFCs entered in use on submarines, the technology was likely introduced via three niche strategies. Firstly, by exploiting this particular customer segment, the prohibitive aspect of road and safety regulations was avoided, thereby corresponding to the 'social redesign' niche strategy.

Secondly, the significant cost of the system was mitigated by selling to a top niche –i.e. the military– which was willing to pay the premium for the product and for its limited production. The situation cannot be considered as a 'subsidized' niche strategy, given that the greater societal benefits were not the main driver behind the governments' decision to sponsor the commissioning of the PEMFC submarine.

Lastly, the use of the submersibles for a dedicated application circumvented the need for massive public deployment of a hydrogen infrastructure altogether; thus, the 'stand-alone' niche strategy being used.

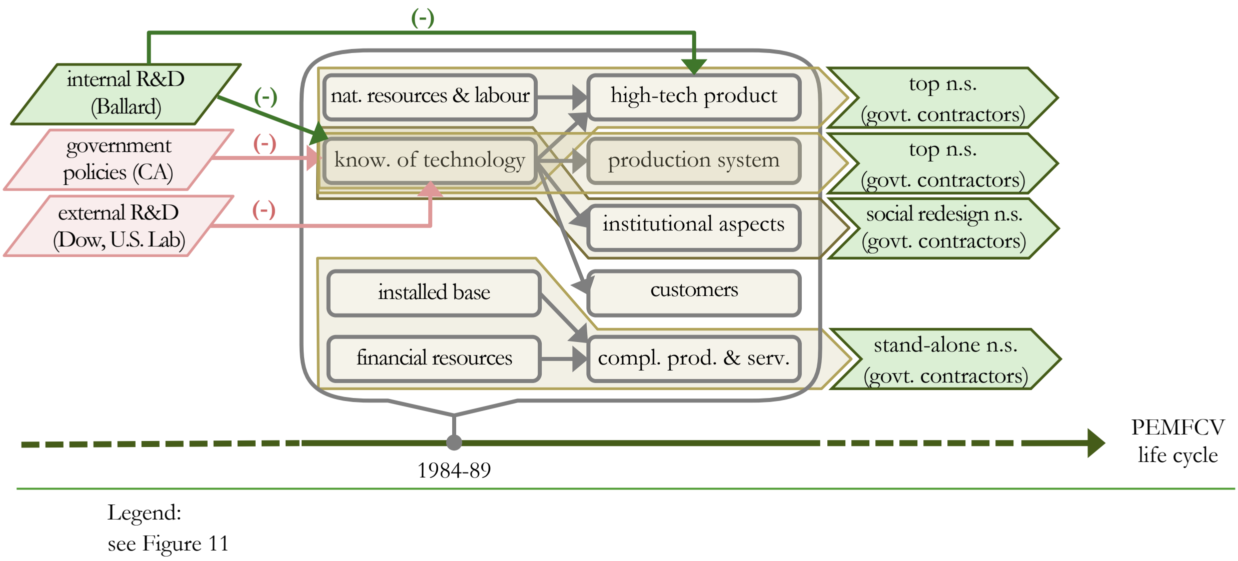


Figure 37: Market context of the PEMFCV technology between 1984-1989

There was no indication that the product application in submarines was used to educate the mainstream market with regard to the benefits of the PEMFC technology in vehicle application.

During the 1980s, the main advancements of the PEMFC systems can be attributed to three actors: Los Alamos National Laboratory, Ballard and Dow Chemical. The U.S. Los Alamos National Laboratory showed the platinum loading for the cell's catalyst could be decimated, i.e. reduced by a factor of 10 (Behling 2013b). Ballard had also "use[d] low cost graphite for the fluid flow field plates, instead of the niobium used in the NASA cell plates" (Prater 1990, p.243). In 1987 and 1988, Ballard tested a new membrane developed by Dow Chemical in the early 1980s, which allowed the cell to produce four times the current compared to that of Nafion at the same cell voltage. Cell durability of over 10,000 h[ours] was also demonstrated" (Behling 2013b, pp.427–428). The Dow membrane also accounted for substantial improvements in size reduction, weight and cost (Prater 1990). Despite these advances, the price for the technology was still prohibitive for a mass market.

In fact, material reduction, material replacement and performance improvement were all important cost reduction measures (Prater 1990). The three factors are featured in Figure 37 as follows: Dow's developments and the findings of Los Alamos National Laboratory as 'external R&D'; while Ballard's advancements as 'internal R&D'. These were not advancements in fuel cell technology which resulted from the application in submersibles. Therefore, they may not be considered as an influence of any niche strategy on the barriers to large-scale diffusion.

The other external factor –government policies– makes reference to initiatives similar to the ones initiated by the Government of Canada, when commissioning Ballard to further the current state of the technology.

EARLY 1990S

Between 1990 and 1993, the former niche strategies for the application in submersibles cannot be considered as active, given that there were no reported similar market introductions, or further advancements targeted at this niche.

For passenger vehicles, the structure of the supply per vehicle manufacturer yields some interesting insights. For instance, Daimler and other manufacturers – e.g. Mazda– had used Ballard fuel cells when experimenting with the PEMFC technology in the early 1990s. This would entail that Ballard received revenue from this transaction, and based on the prohibitive price and low production volumes, the company would have employed the 'top' niche strategy. Furthermore, since the product applications were demonstrated in public with the scope of furthering the knowledge on the technology, Ballard would have likely used the 'demo, experiment and develop' niche strategy.

However, these conclusions would be erroneous. Firstly, note that Ballard received revenue, rather than the PEMFCV manufacturer. In fact, Ballard should be seen as a supplier of PEMFC stacks, and therefore it receiving revenue would not constitute the requirement for the technology –i.e. the PEMFC vehicle, not the PEMFC stack– to have been introduced via a niche strategy. In the earlier situation of submarines, the military contractor would have generated revenue, regardless of which supplier –Siemens or Ballard– had provided the fuel cell stack. To further illustrate the erroneous logic, take the strategic alliance of Daimler, Ford and Ballard in the late 1990s (Behling 2013b). Under this partnership arrangement the fuel cell stack manufacturer –Ballard– would not have continued to receive revenue from Daimler, which would have indicated an abrupt end to the 'top' niche strategy simply as a result of a different alignment in the industry vertical.

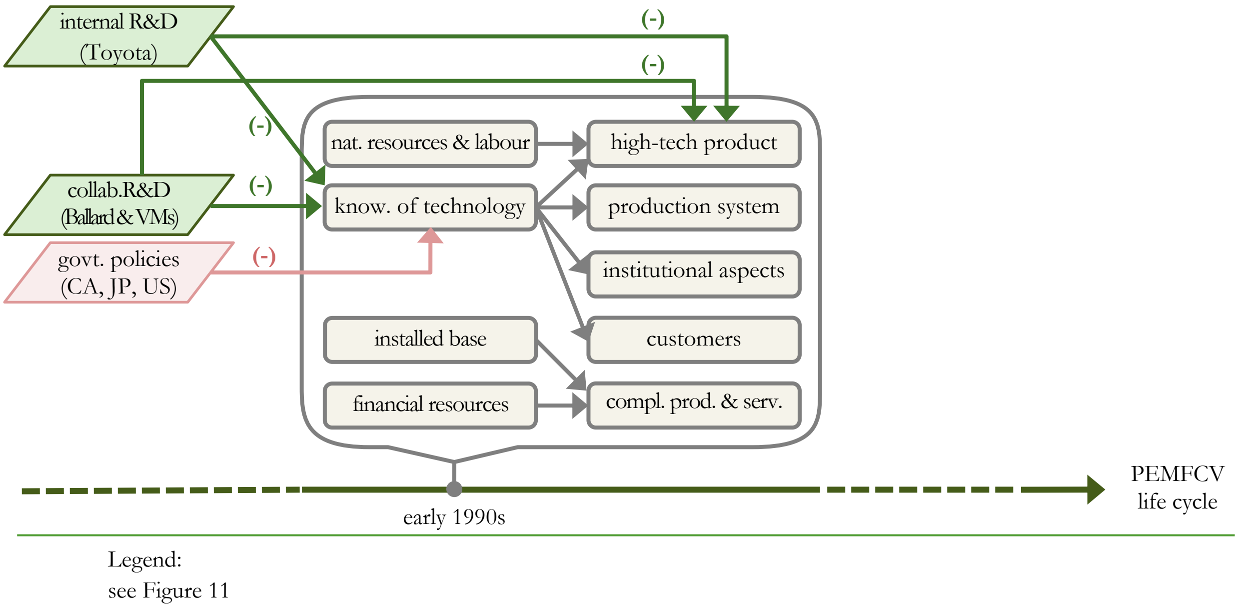


Figure 38: Market context of the PEMFCV technology in the early 1990s

The factor 'collab[orative] R&D' captures the influence of the technological developments conducted by Ballard in partnership with vehicle manufacturers such as: New Flyer, or Daimler, etc.

Toyota, on the other hand, began developing its proprietary technology in-house starting with 1992. The target advancements were in the area of materials, components, control systems and production technology (Toyota Motors 2004). These projects were part of Toyota's internal R&D strategy.

Vehicle manufacturers had learnt from the R&D efforts –collaborative or in-house– performed in the early 1990s, since they were able to release the first passenger car versions during the mid-1990s. The effect on the core factor 'new high-tech product' refers to performance improvements.

"The toughening of environmental regulations in North America pressed automobile manufacturers operating in that market to establish long-term environmental strategies, and thus they set about developing fuel-cell vehicles […] In Japan, industry-related organs of the government, perceiving the need to support automakers, electronics manufacturers, and other domestic industries, began actively pursuing policies aimed at supporting PEFC research and development and promoting the spread of PEFC use" (Maeda 2003, p.2). These developments would suggest that more government policies would be deployed in this respect around the world, in addition to the funding from the Canadian government: U.S. from 1990 (see Fuel Cell Today 2012b), Japan from 1992 (see Maeda 2003).

1993-1995

Public transport buses generally have "fixed routes, centralized fueling and maintenance infrastructures, and dedicated maintenance personnel" (Behling 2013b, p.430). In applying the PEMFC technology to public transport buses, the core factor of 'complementary products and services' was circumvented by making it possible to build-up a dedicated system based on the fixed route pattern of buses, i.e. 'stand-alone' niche strategy.

The development of hydrogen buses –in particular those operating on the basis of the PEMFC technology– is connected to the level of demand shown by city authorities (Ball et al. 2009). "They favoured the buses for their low pollution [i.e. zero emissions] as well as for social reasons, such as raising public hydrogen awareness and promotion of further research" (Ball et al. 2009, p.257). In fact, all public transport buses can be seen as initiatives to educate customers with respect to the hydrogen technology and its benefits. In cases where there exists an alignment between the subsidizing government body and the OEM, the 'demo, experiment and develop' niche strategy is also used. For instance, when hydrogen buses were first developed by Ballard in 1993, and soon-after in 1995, several government bodies of Canada "implemented a government-industry cost-share program to develop a PEMFC-powered bus […] and the Canadian government reportedly invested a total of $4.84 million" (Behling 2013b, p.428).

The government policy can be seen to have influenced to some extent also the institutional barriers. If public buses running on hydrogen were desired by the Canadian officials, then it would imply that they were willing to grant road certification to such experimental vehicles and therefore create precedent for other similar PEMFCV introductions.

As late as the early 2010s, the cost of PEMFC buses was fivefold than that of a diesel bus. Combined with the costs of the dedicated hydrogen infrastructure it meant that "they [were] only used where a city deem[ed] the environmental benefit to be worth the extra investment" (Fuel Cell Today 2012b). It would mean that the factors affecting the product's price were circumvented by adopting a subsidized niche strategy, given the positive societal benefits described before.

Ballard improved the performance of the technology: from the first P1 bus version to the P2. The external factor capturing this effect is represented by "collab[orative] R&D" featured under Figure 39, since the fuel stack manufacturer engaged with vehicle manufacturers –i.e. New Flyer, Daimler, etc.– to develop the PEMFCVs. On the other hand, Toyota continued its in-house developments, as featured by the factor 'internal R&D'.

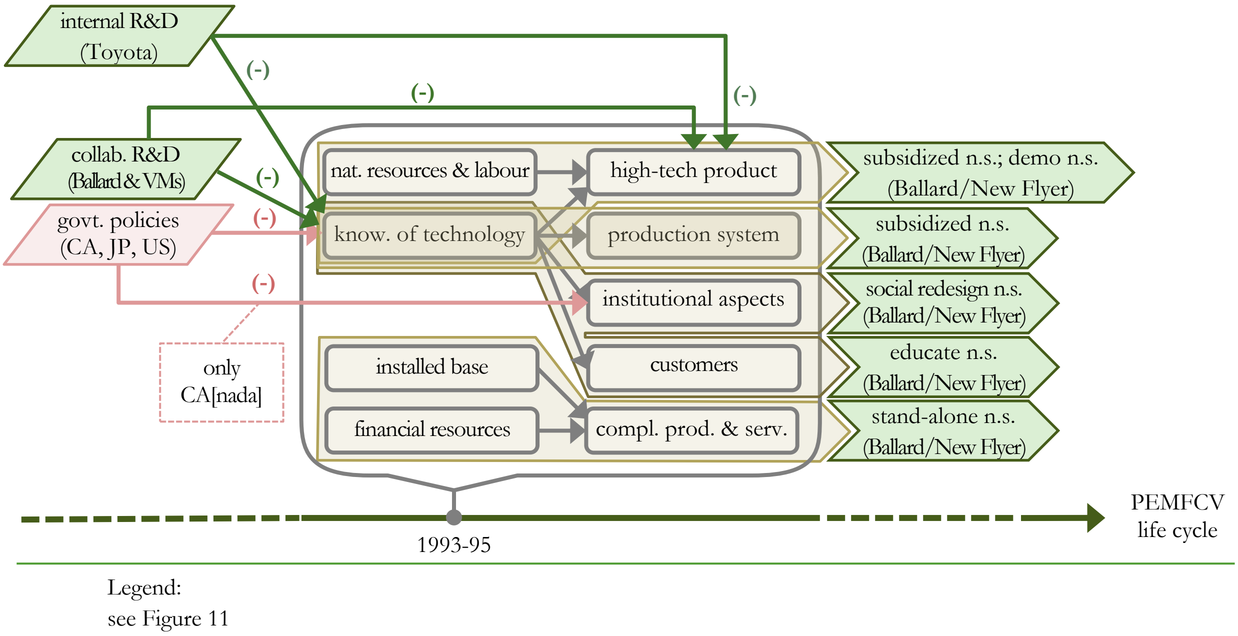


Figure 39: Market context of the PEMFCV technology between 1993-1995

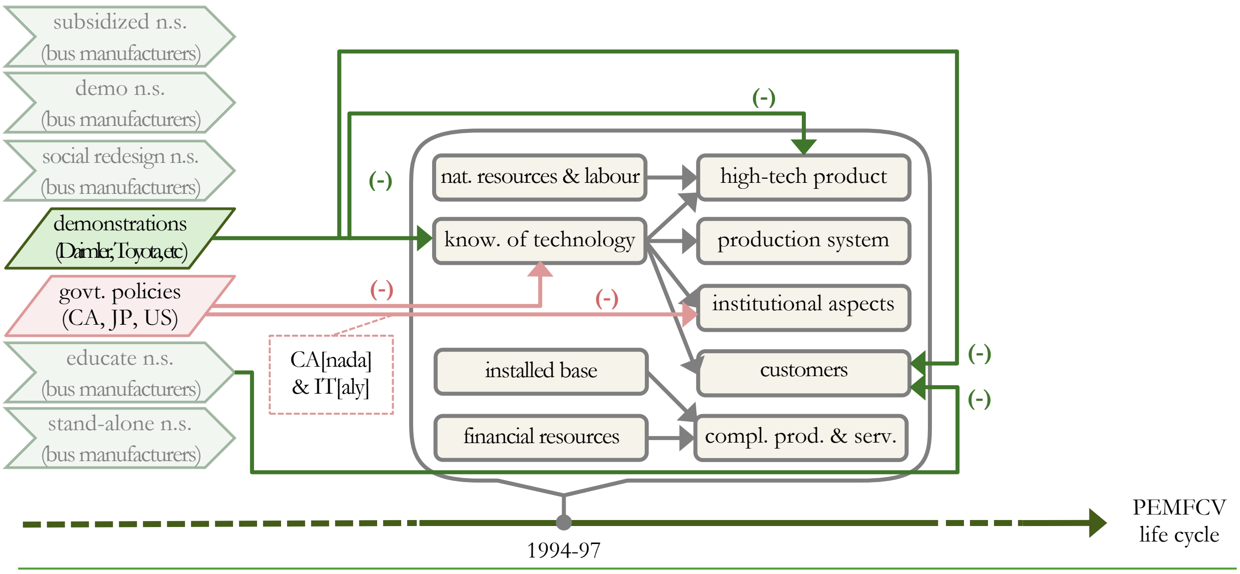
In almost each of the following years new public PEMFC buses were being developed and/or deployed (see Behling 2013b; FuelCells.org 2015), arguably using the similar niche strategies as above. Thus, the niche strategies from Figure 39 will be featured in the later years.

1994-1997

"In April 1994, Daimler surprised the world with its first New Electric Car (NECAR) incorporating an improved version of the Ballard stack that was used in the P2 bus" (Behling 2013b, p.428). Thus, it would appear that the earlier R&D by Ballard in the P2 bus, was helpful in advancing the knowledge of the technology.

With its NECAR1 vehicle, "Daimler proved to the world audience the basic suitability of the fuel cell technology as an electric vehicle propulsion system" (Behling 2013b, p.428). Hence, the vehicle was instrumental in educating the customers with respect to the technology, as represented in Figure 40 by the influence of the external factor 'demonstrations'.

Later on, "[i]n May 1996, Daimler and Ballard demonstrated the world's first passenger [given that the NECAR1 was in fact a cargo van] car with PEMFC drive, the NECAR 2" (Behling 2013b, p.428). However, as before, there was no revenue generated from the product introduction.



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see Figure 11

Figure 40: Market context of the PEMFCV technology between 1994-1997

2002-2004

In 2001, public road testing of passenger PEMFCVs began in California (U.S.A.) and Japan –by Honda (Honda Motor Company 2015b), Toyota (Toyota Motors 2004), and later others. Given that these vehicles were granted public road certification, it created a precedent for the lessening of the institutional barriers for the introduction of PEMFCV on public roads.

Starting with 2002, some vehicle manufacturers (VMs) began leasing their PEMFCVs to government or corporate customers: Toyota FCHV from December 2002 (Toyota Motors 2004), Honda FCX from December 2002 (Honda Motor Company 2015a; Honda Motor Company 2015c), Nissan from December 2003 (Behling 2013b), etc. The automobile manufacturers targeted geographical areas where the institutional environment was favourable –see previous paragraph– and where there existed a sufficiently developed hydrogen infrastructure; hinting that the geographical niche strategy had been used to circumvent the corresponding market situations.

"[T]hese vehicles [were] made available by manufacturers to gain experience ahead of a commercial launch planned from 2015" (Fuel Cell Today 2012b). From this perspective, it becomes reasonable to conclude that the automakers had also used a 'demo, experiment and develop' niche strategy to learn about the vehicle's operation in traffic. Also, the educating role of (not only) these projects towards consumers' knowledge of the technology was likely acknowledged by vehicle manufacturers (see Toyota Motors 2004, p.18).

Lastly, to circumvent the prohibitive price of ownership of a PEMFCV, the automakers employed a niche strategy which is not listed in the generic list of ten niche strategies by Ortt et al. (2013). The vehicles were leased to customers, rather than being sold for their full ownership price. This represents another way to overcome the cost barriers of radically new high-tech products in the automotive industry. Actually, consumers might have paid only for the usage rights over the technology, without the option of exercising ownership at the end of the lease. For instance, the U.S. company website of Hyundai Motor America mentioned that "at this time the vehicle [i.e. Tucson Fuel Cell] is only available for lease. In addition, there is no purchase option at the end of the lease" (Hyundai Motor America 2015).

Both by 'leasing' the PEMFCVs and by experimenting with them in a market context –'demo, experiment & develop'– the manufacturers increased the installed base, as shown in Figure 41. Via this action, the VMs would indirectly (positively) influence the future availability of a hydrogen infrastructure.

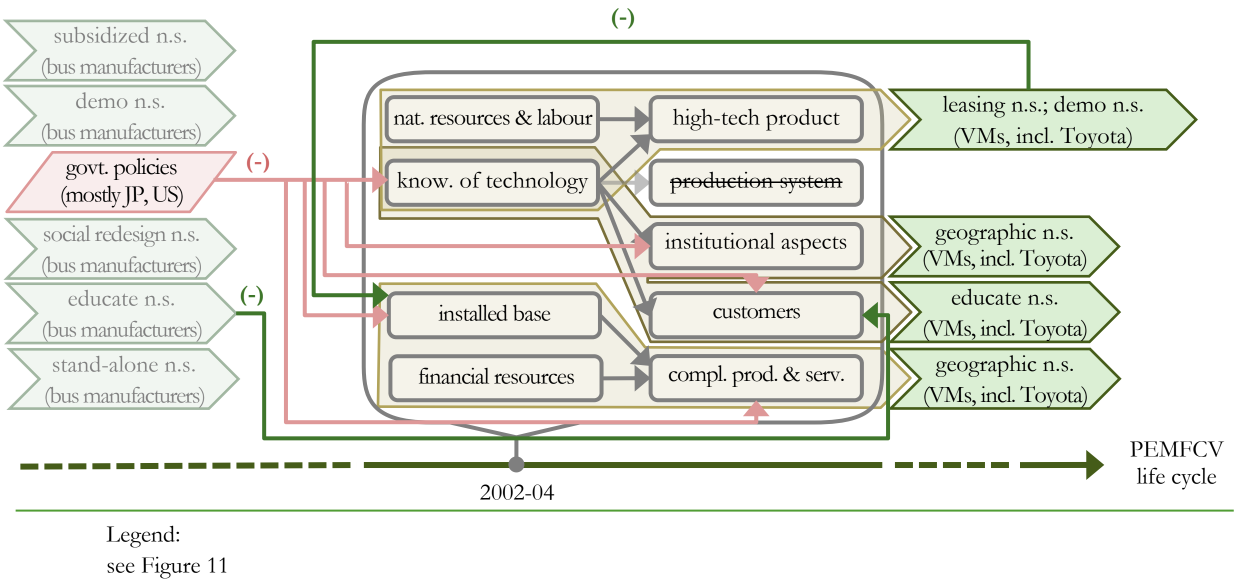

Figure 41: Market context of the PEMFCV technology between 2002-2004

New manufacturers of buses emerged, for example: "FCHV-BUS2 [developed by Toyota and Hino (Toyota Motors 2004)] municipal model became the first fuel cell bus to go into revenue service as part of a municipal fleet in Tokyo [and Japan for that matter] starting in August 2003" (Behling 2013b, p.448). Government policies continued to provide funding for public transport buses: "In March 2001, two major demonstration projects were unveiled […] the European Union Fifth Framework Program (FP5) project, 'Clean Urban Transport for Europe (CUTE)' […] Both projects aimed to operate hydrogen buses in inner cities. The projects were due to start in late 2002 and run for 2 years" (Behling 2013b, p.444). To sum up, introductions of public transport buses continued, employing the same niche strategies as before.

Lastly, government policies aimed at increasing the knowledge of technology continued: "[a] large project named JHFC [was] underway in Japan to investigate in detail the energy effectiveness, environmental burden and other aspects of fuel cell vehicle use. Toyota, Nissan, Honda, DaimlerChrysler, GM, Hino, Mitsubishi, and Suzuki are participating to collect basic data through fuel cell vehicle trials on public roads. Also participating are fuel producers who may supply hydrogen in either gas or liquid form at their fueling stations" (Toyota Motors 2004, p.18).

Between 2002 and 2010, the JHFC "held many types of events with the aim of letting more people know more about FCVs" (JHFC 2011b). Thus, government policies were also trying to educate consumers on the topic of FCVs, and implicitly PEMFCVs.

These policies were instrumental in stimulating the development of the hydrogen infrastructure and installed base. In Japan, for instance, between 1999-2003 "emphasis was placed on distributed hydrogen utilization technologies, and demonstration testing was conducted on hydrogen storage technologies and hydrogen supply stations" (Maeda 2003, p.7). The Japanese government helped increase the installed base –and therefore depress the impact of this contextual factor on the complementary products and services– in two ways: firstly, it commissioned public PEMFC buses, and secondly it became a lessee of PEMFC passenger vehicles. In the U.S., analogue programs were the California Fuel Cell Partnership and the California Hydrogen Highway.

2004

Warehouse operators require an in-house hydrogen fuelling station (FuelCells.org 2012) to operate the forklifts within the company premises. This corresponds to the 'stand-alone' niche strategy.

The price of PEMFC forklift is arguably higher as compared to the traditional material-handling equipment, since Behling (2013b, p.530) notes that this "sector appears to be a niche where the advantages of fuel cells serve user needs so well that the cost disadvantages can be tolerated." Therefore, we may conclude that manufacturers make use of the top niche strategy to circumvent the cost barrier of the new high-tech product.

The market was primarily concentrated in North America (see FuelCells.org 2012; Behling 2013b; Curtin & Gangi 2013), but the reasons for this occurrence were not made explicit by the case literature. Thus, we may not conclude that it corresponds to a 'geographic' niche strategy.

Lastly, by using the PEMFCVs only on the operators' premises they would not have to qualify to regular road standards. Thus, via the 'social redesign' niche strategy the forklift and fuel cell manufacturers explored an application where institutional aspects were more favourable.

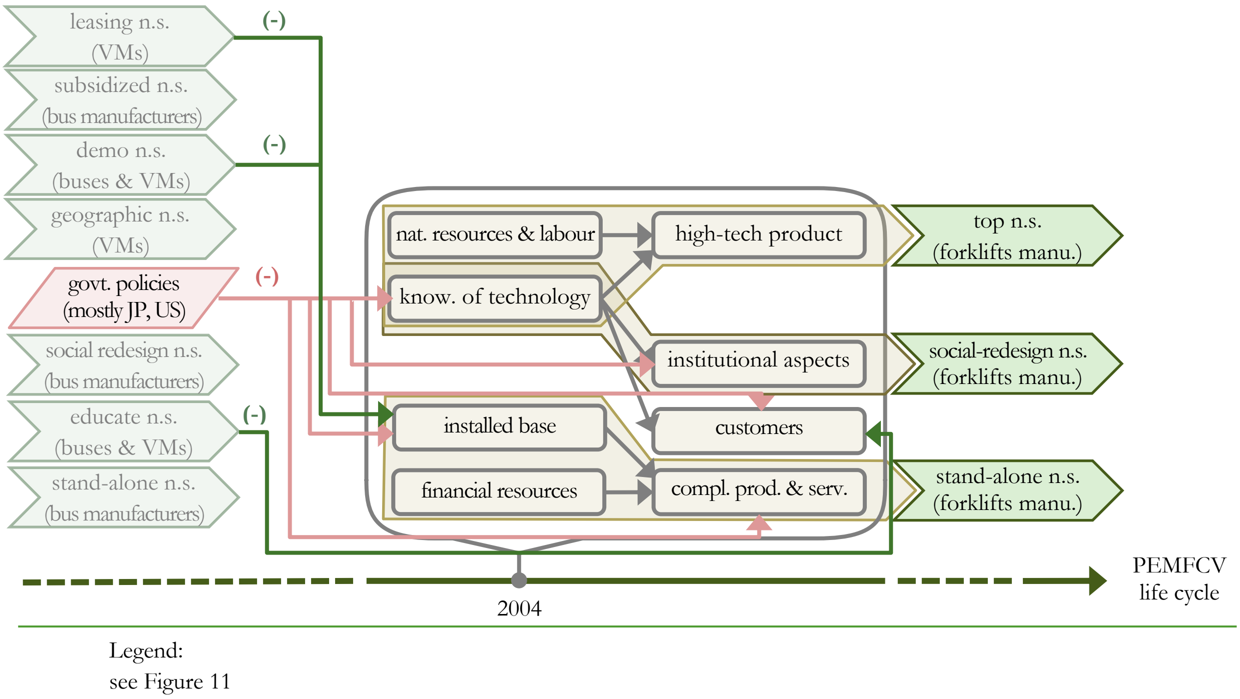

Figure 42: Market context of the PEMFCV technology around the year 2004

2005-2013

During this period the cumulative number of leased PEMFCVs increased (see Behling 2013b). The geographic targeting of consumers on the basis of an available hydrogen refuelling infrastructure continued, as illustrated for instance by the leasing election criteria of vehicle manufacturer Honda: "[t]he initial criteria for fuel cell vehicle ownership [i.e. leasing], including proximity to hydrogen refueling stations […] played a part in Honda's customer selection process" (Honda Motor Company 2008a).

In 2007-2009, based on a limited selection of survey, it was reported that "[t]he consumer acceptance in the transport sector seems to be no barrier to the introduction of hydrogen. All analysed studies show that there is a great acceptance, but a low knowledge level for hydrogen technologies" (Ball et al. 2009, p.268). Nevertheless, some manufacturers –Honda for instance– continued to educate the consumers with regard to the product's benefits: "[n]umerous FCX Clarity events are to be held beginning in 2009 at which the public will have the opportunity to come in contact with the FCX Clarity and gain a greater appreciation of the appeal of fuel cell vehicles" (Honda Motor Company 2008b). Therefore, the barrier to large-scale diffusion was more likely to have still existed even throughout the late 2000s.

During the same period, sales of materials handling vehicles were subsidized by as much as half of the total deployment costs (Behling 2013b). Nevertheless, "[o]ut of a total 2230 forklifts sold since 2004 thru June 2011, 1628 (73 percent) were sold independently of […] subsidies" (Behling 2013b, p.540). These buyers represented the top niche that was willing to pay the associated premium.

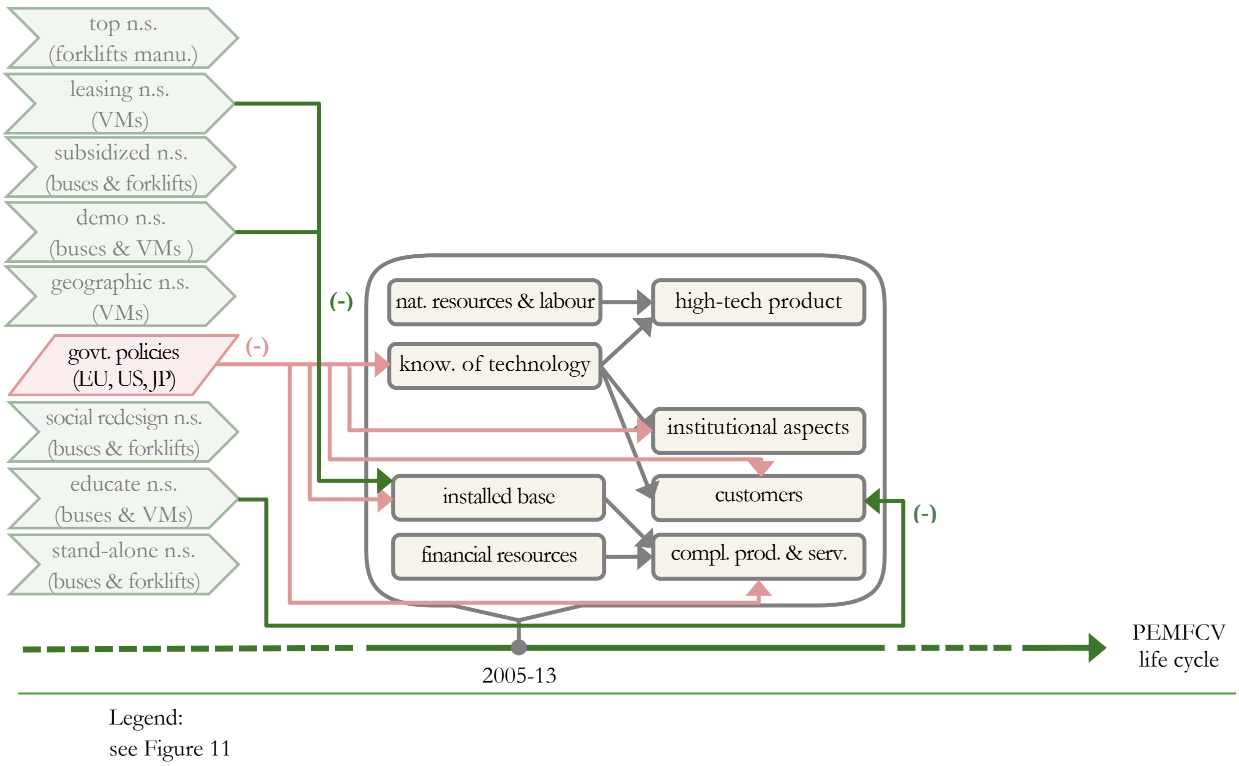

Figure 43: Market context of the PEMFCV technology between 2005-2013

The JHFC project continued until 2010-2011 (JHFC 2011a; JHFC 2011b), thereby substantiating the influence of the external factor 'government policies' on 'knowledge of technology', 'customers' and 'complementary products & services' from Figure 43. Introductions of public transport buses also continued, thus the influence on institutional aspects. The government (subsidy) programmes for leased PEMFCVs can also be seen to have had the same impact on institutional aspects, facilitating the introduction of such vehicles on public roads.

In Norway, the HyNor project was funded by private companies (incl. infrastructure providers), cars owners and government bodies (HyNor 2011). In addition to demonstrations projects, a limited hydrogen infrastructure was set up between 2006 and 2011. Similar projects were carried out in neighbouring Denmark and Sweden. Together the three initiatives form the Scandinavian (SCA) Hydrogen Highway Partnership, which is "backed with strong public and private support in terms of funding, attractive financial tax exemption schemes and investments" (Scandinavian Hydrogen Highway Partnership 2015). As of 2007, the German government has also committed funds to infrastructural investments in hydrogen stations, fuel cell vehicles fleets (incl. public transport buses), and R&D (Bonhof 2011). All these initiatives will be generically grouped under Figure 43 as government policies undergone in the European Union, i.e. EU.

Lastly, the influence of 'demo, experiment and develop' or 'leasing' niche strategy on the installed base continued; the same can be said about government policies. These effects are highlighted in Figure 43.

2013-2015

In 2013, the cost of platinum estimated for Toyota's 2015 PEMFCV was estimated to contribute to less than 3% of the total vehicle costs, i.e. equivalent to 30g of platinum for 2013 market prices (Carter 2013). Given that "it doesn't represent a prohibitive cost by any means" (Carter 2013), the contextual factor 'natural resources and labour' had stopped to influence the core factor 'new high-tech product', specifically its price.

At over US$57,500 (Toyota Motor Sales USA 2015), the price of the vehicle remains prohibitive. A 3-year leasing options was available, and in the state of California the car was potentially eligible for US$5,000 state rebate (Toyota Motor Sales USA 2015). Therefore, the Toyota Mirai will be sold via a subsidized niche strategy, and the remainder of the price tag will be addressed by either a top niche strategy –for customer willing to bear the costs of adoption– or by a leasing niche strategy for those less affluent.

In 2014, "[t]o support the impending roll-out of hydrogen fueling infrastructure and Fuel Cell Electric Vehicles (FCEV), SAE International's Fuel Cell Standards Taskforce has completed two technical standards: SAE J2601, "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles"; and SAE J2799, "Hydrogen Surface Vehicle to Station Hardware and Software". The standards have been created to harmonize hydrogen fueling worldwide for both 35 MPa and 70 MPa pressures" (BioAge Group 2014). In addition, the number of road certifications for PEMFCVs increased both within U.S. –New York, Connecticut (Fuel Cell Today 2012b)– and outside of U.S. –e.g. Western Europe (see Curtin & Gangi 2013). Thus, we may conclude that the institutional barriers had disappeared. Although this eliminated the need for a geographical niche strategy from this perspective, the lacking hydrogen infrastructure would still require it. The need for social redesign was also eliminated.

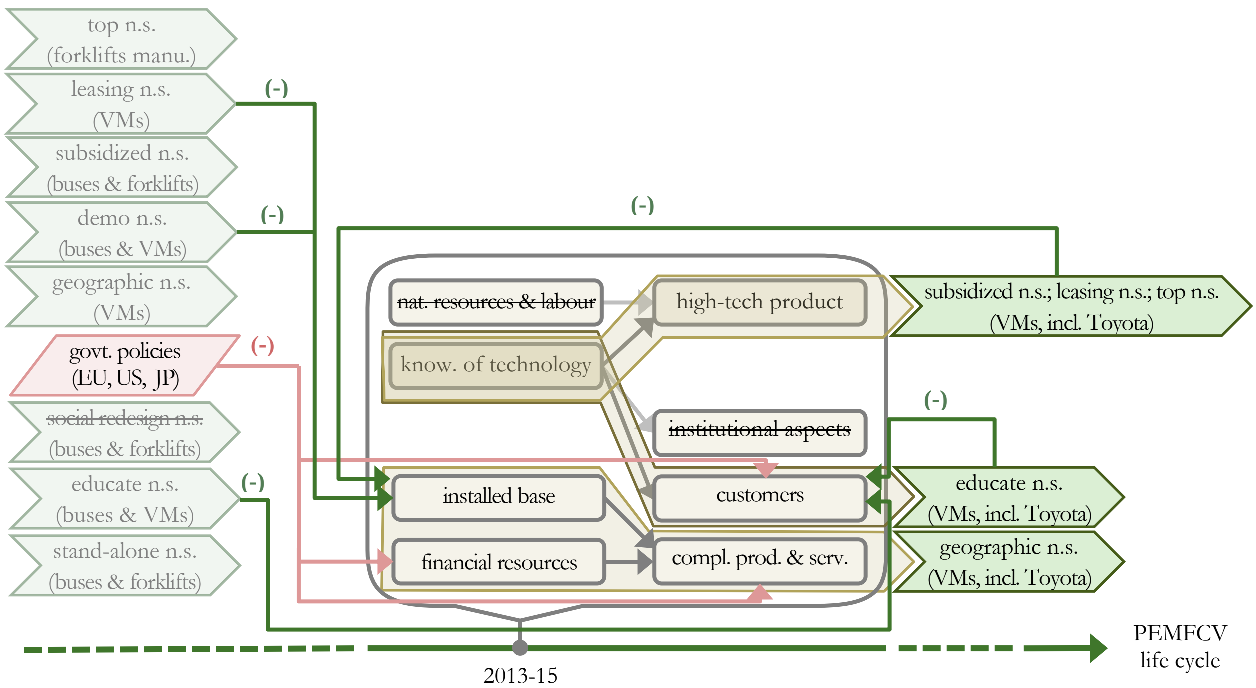

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Figure 44: Market context of the PEMFCV technology after 2013 and up to 2015

Judging by the marketing materials (see Toyota Motor Sales USA 2015; Hyundai Motor America 2015) of vehicle manufacturers with regard to fuel cell technology during the corresponding period, it would appear that there is still lacking knowledge of technology among consumers; thereby the newly introduced PEMFCVs would continue to steer the education of customers concerning the vehicle technology.

In 2014, in the U.S., regional government committed to the subsidy of "$46.6 million to accelerate the development of publicly accessible hydrogen refueling stations in California in order to promote a consumer market for zero-emission fuel cell vehicles." (California Energy Commission 2014) In addition, one year earlier, a bill had been passed which "include[d] a provision to fund at least 100 hydrogen stations with a commitment of up to $20 million a year" (Xiong 2013). This aspect is captured by the influence of external factor 'government policies' on the contextual factor 'financial resources' and the core factor 'complementary products & services'.

SUMMARY

Figure 45, Figure 46 and Figure 47 present the series of market contexts and niche strategies during the market adaptation phase, including all of the formerly explained effects of niche strategies or external factors on the core and contextual factors.

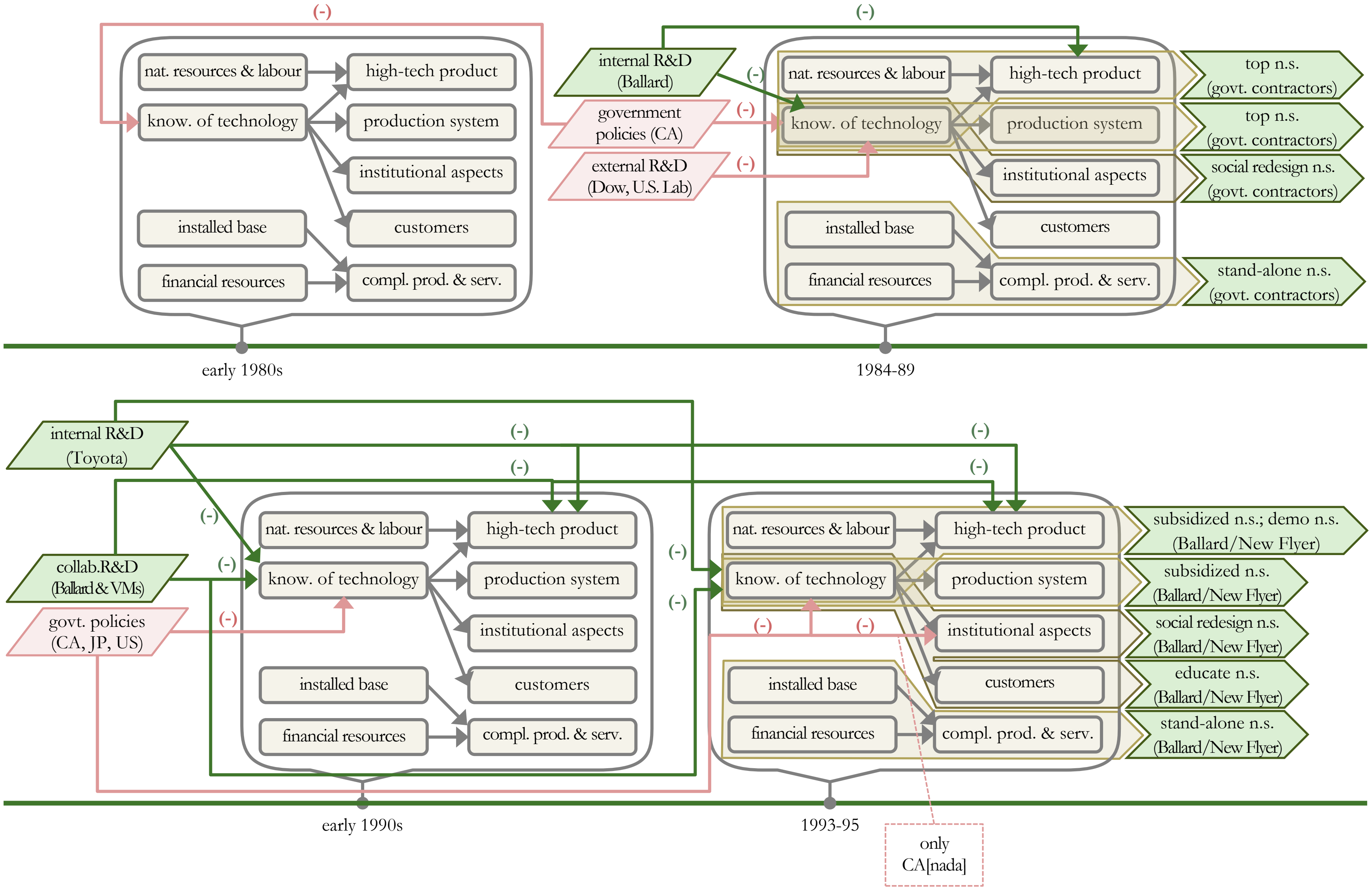

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Figure 45: Chronology of market contexts, niche strategies and external factors – Part 1/3 – PEMFCV technology

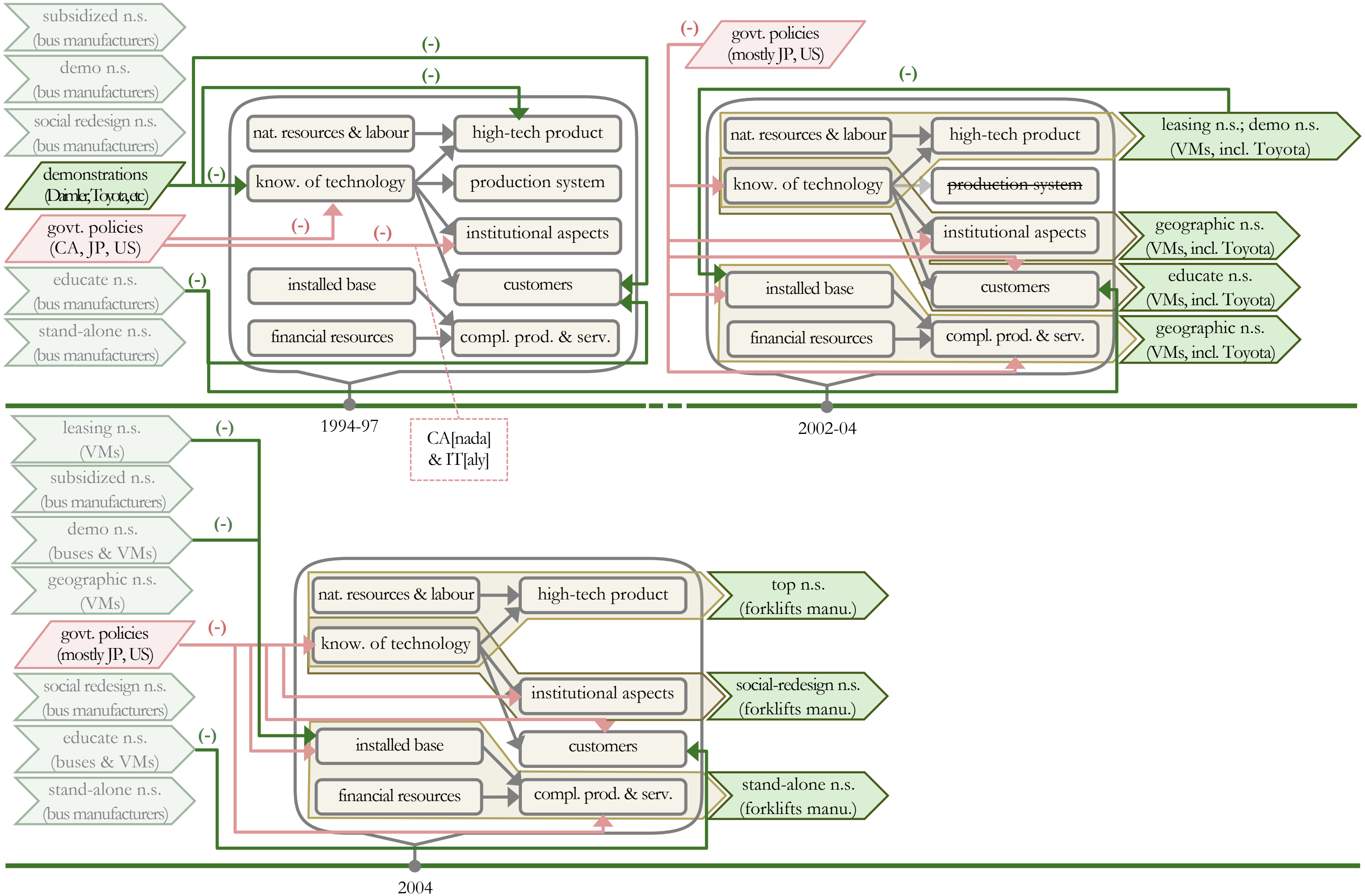

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Figure 46: Chronology of market contexts, niche strategies and external factors – Part 2/3 – PEMFCV technology

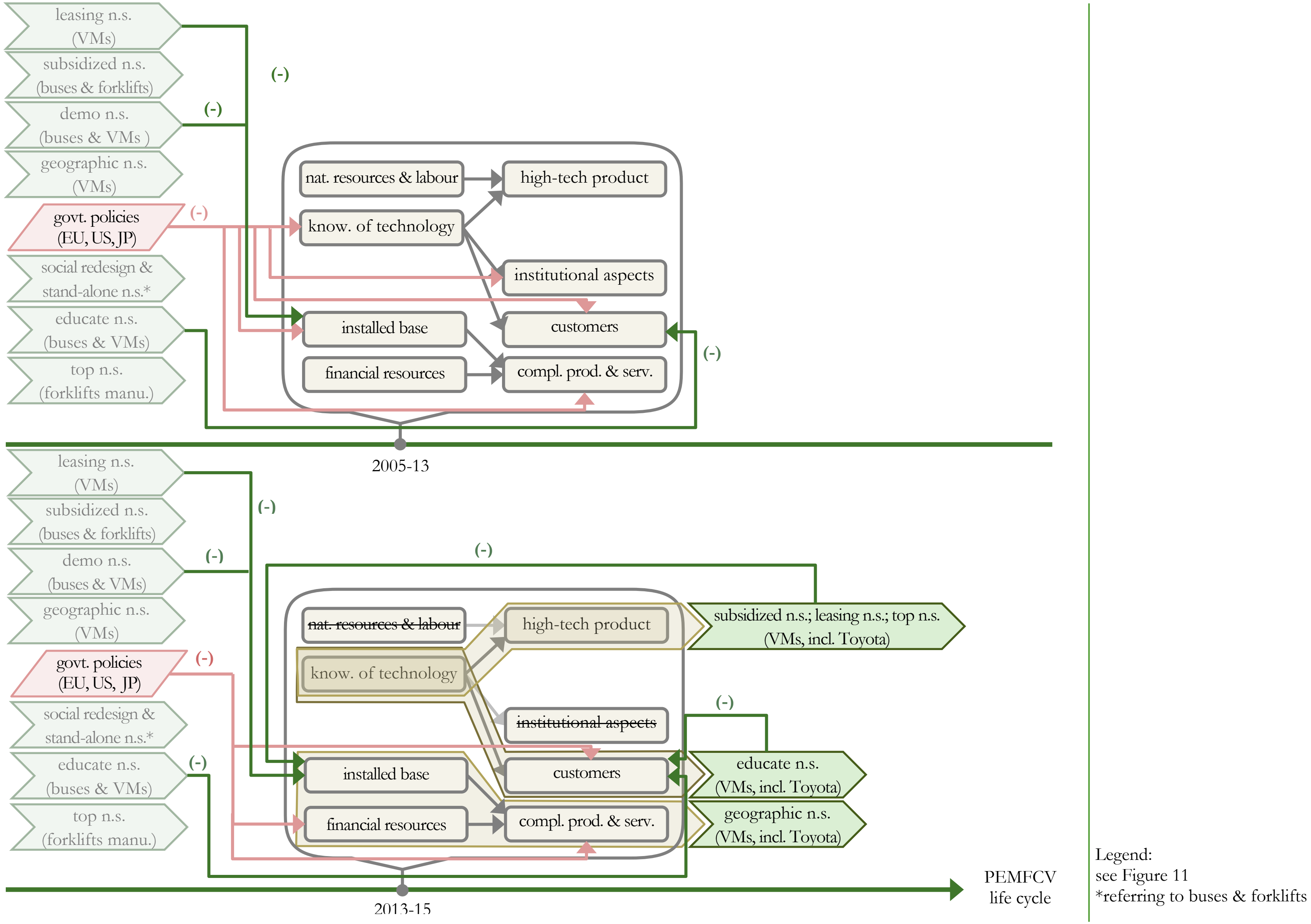


Figure 47: Chronology of market contexts, niche strategies and external factors – Part 3/3 – PEMFCV technology

5.3.4. CHANGE IN THE BARRIERS TO LARGE-SCALE DIFFUSION

4.A Depict graphically the change in the core factors throughout the market adaptation phase

Figure 48 visualizes the change in the core factors hampering large-scale diffusion for the case of the PEMFCV technology, based on the more detailed qualitative –and at times quantitative– explanations from section 5.3.3.

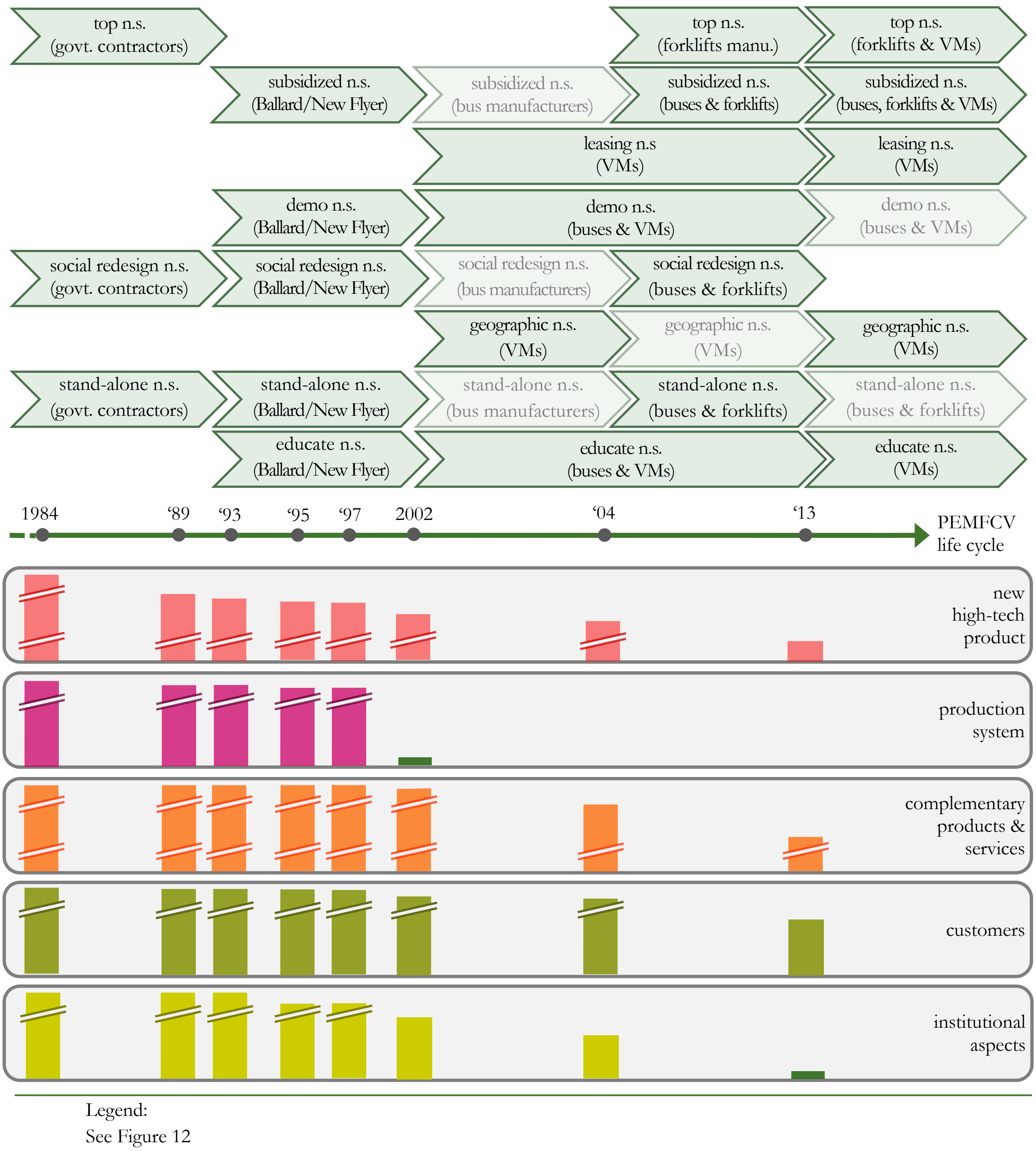


Figure 48: Dynamics of the core factors hampering large-scale diffusion – PEMFCV technology

4.B How did the barriers to large-scale diffusion change over the span of the market adaptation phase?

The barriers to large-scale diffusion were present from the beginning of the market adaptation phase, and all but one of the core factors were influenced by the lacking knowledge of the technology. Natural resources and labour influenced the prohibitive price of the new high-tech product up to roughly the year 2013.

Qualitatively speaking, all of the barriers decreased in magnitude during the investigated period. Two of the barriers had disappeared by 2013 –or earlier– already; three of them, however, remained active up to the time of writing.

Among these remaining barriers, the most influential remains the lack of complementary products, i.e. a hydrogen refuelling infrastructure. It was influenced by a separate set of contextual factors than the other barriers, i.e. financial resources and installed base.

4.C What was the influence – if any – of niche strategies on the barriers to large-scale diffusion?

As opposed to the previous two cases, niche strategies did not contribute towards increasing the magnitude of any of the barriers. The product introductions were arguably important in (partially) removing the barriers, but because of the multitude of niche strategies active at one-time, the influence of each strategy on the barriers to large-scale diffusion was predominantly difficult to isolate.

Nevertheless, some effects could be isolated. For instance, when manufacturers introduced PEMFC passenger vehicles in the early 2000s and continuing up to 2015, they were essentially increasing the installed base. With more passenger cars on the market, hydrogen refuelling stations would have had an incremental positive incentive to be built. Although this is only an indirect effect on the barrier of 'complementary products and services', it does show how niche strategies –in this case 'leasing' and 'demo, experiment and develop' at first; followed by 'subsidized' and 'top' niche strategies around the year 2015– may be used to stimulate the infrastructure development.

A direct effect on the barriers was observed for the 'educate' niche strategy, specifically on improving the customer knowledge with respect to the PEMFCV technology. This was done initially via the product introduction in public buses and later on by that of passenger vehicles.

4.D Were there any external factors – i.e. apart from niche strategies – which had an influence – i.e. remove / create – on the barriers to large-scale diffusion?

Government policies were instrumental in furthering the knowledge of the technology, either by proposing clear targets to be met –e.g. Japan's Hydrogen and Fuel Cell Demonstration Project– or by subsidizing research projects and consumer adoption. The most prevalently cited ones were in Japan and the U.S. Across the board the policies were coupled with industry-government partnerships.

A more interesting observation is the large array of contextual and core factors that were influenced by government policies. Furthermore, the limited hydrogen infrastructure was mainly developed in such areas, for instance California (in the U.S.) or Japan. The main implication is the importance of industry-government collaborations in automotive for the case of disruptive technologies.

Autonomous developments –i.e. external R&D– once again influenced the contextual factor 'knowledge of technology', which in turn helped reduce the impact of the 'natural resources and labour' requirements. Internal R&D on the other hand was either done by central actors within their network –for e.g. Toyota– or in collaborations with PEMFC stack manufacturers and automakers –for e.g. Ballard and Daimler. The case does not offer sufficient information to assess which of the two has a more pronounced impact on the barriers.

Demonstration projects by vehicle manufacturers were also impactful with regard to the level of technology knowledge. Because they couldn't be classified as revenue-deriving activities, they were not listed as niche strategies. Under the cupola of demonstration projects, the internal R&D of the companies involved in the PEMFCV development could also be included.

4.E Why did the barriers to large-scale diffusion change over the market adaptation phase?

In conclusion, the change in the barriers to large-scale diffusion over the span of the market adaption phase can be explained by two aspects. Firstly, external factors –such as autonomous improvements or demonstration projects– played a role. Secondly, niche strategies had some influence over the barriers, but even from a qualitative standpoint it is cumbersome to distinguish the impact of the niche strategies from that of the external factors. Combined, these factors resulted in the complete or partial removal of core and contextual factors.

5.3.5.SEQUENCE OF NICHE STRATEGIES

5.A Depict visually the series of niche strategies.

The vehicle manufacturer –e.g. Toyota, Honda, Daimler, etc.– is best regarded as the central actor for the PEMFC passenger vehicles, whereas the fuel stack supplier –e.g. Ballard– befits this role better in the case of public transport PEMFC buses. The subsequent niches correspond to the subsequent product introductions and product continuations.

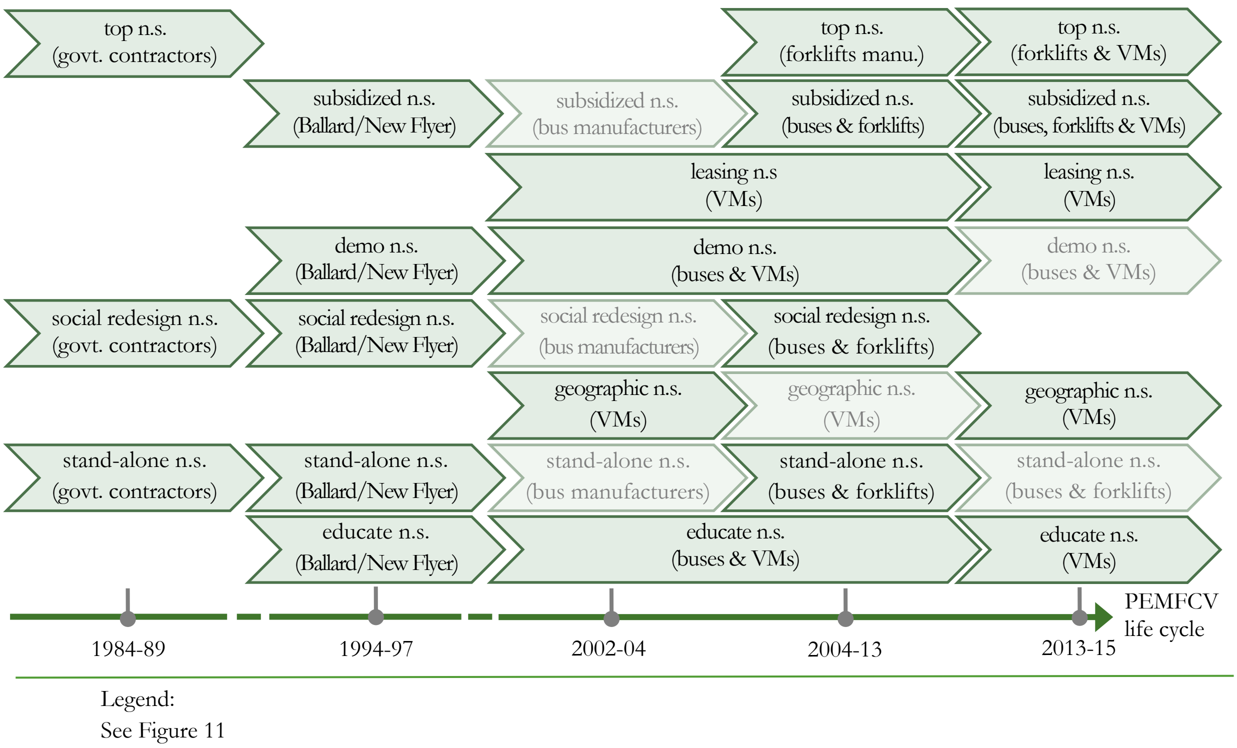
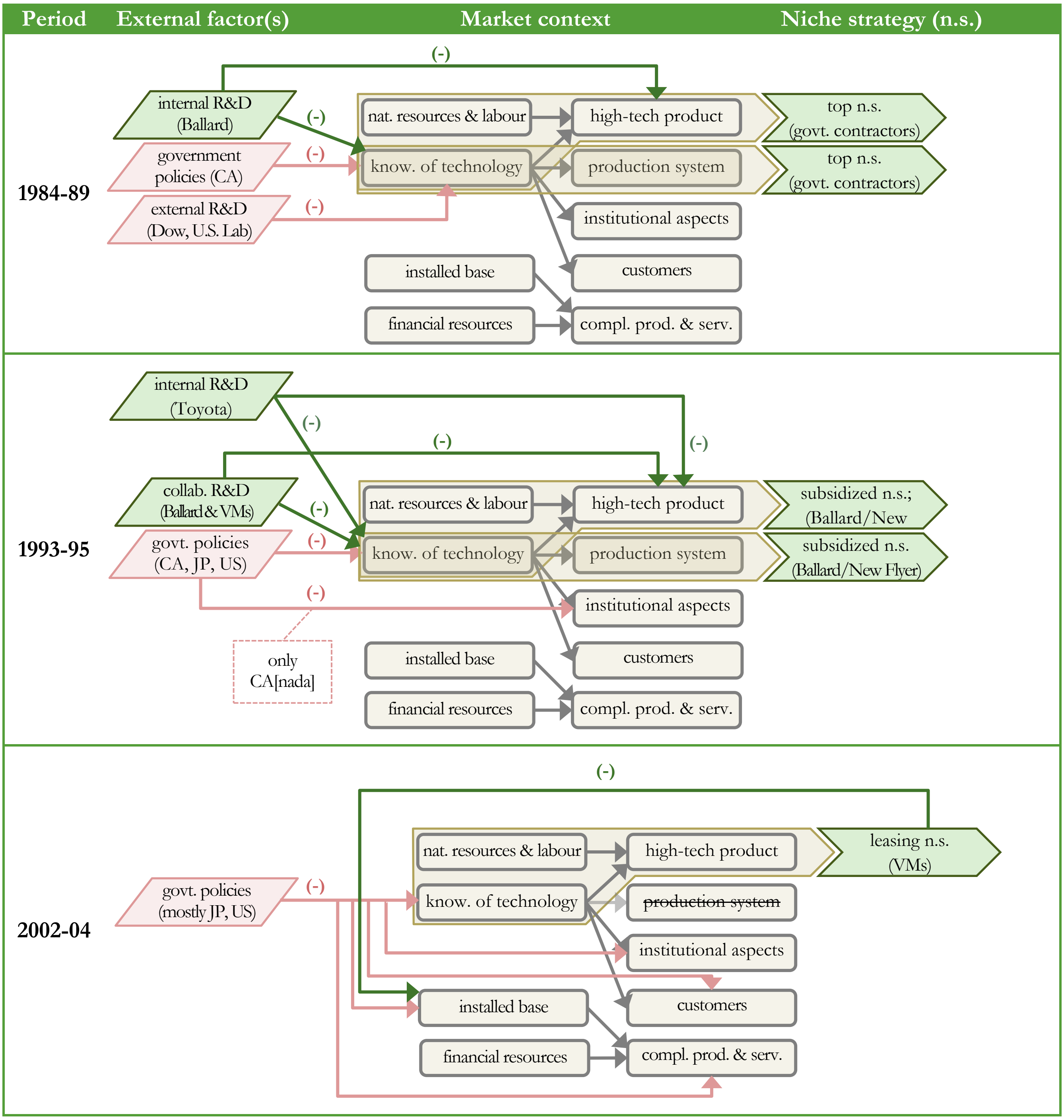
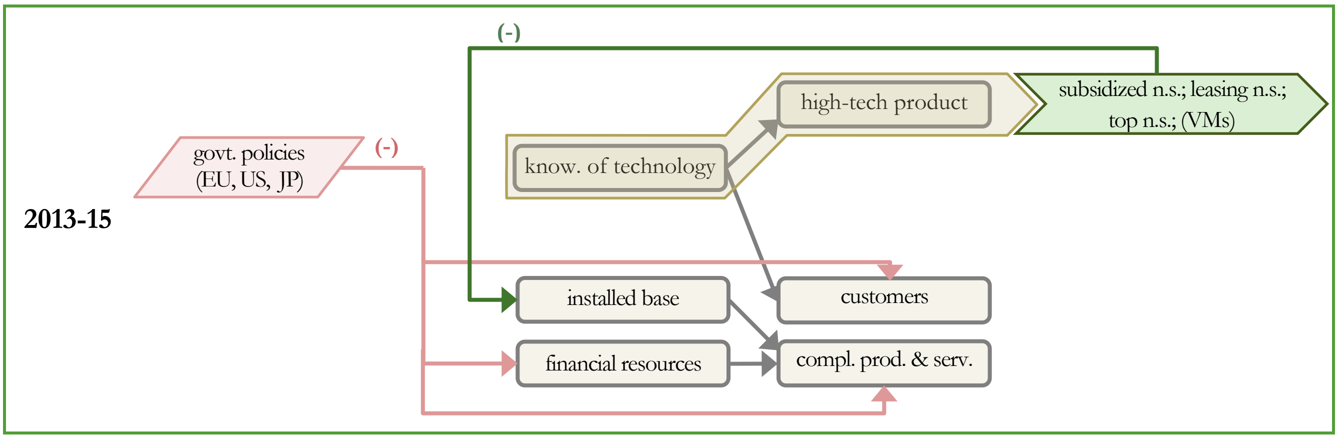


Figure 49: Chronology of niche strategies - PEMFCV technology

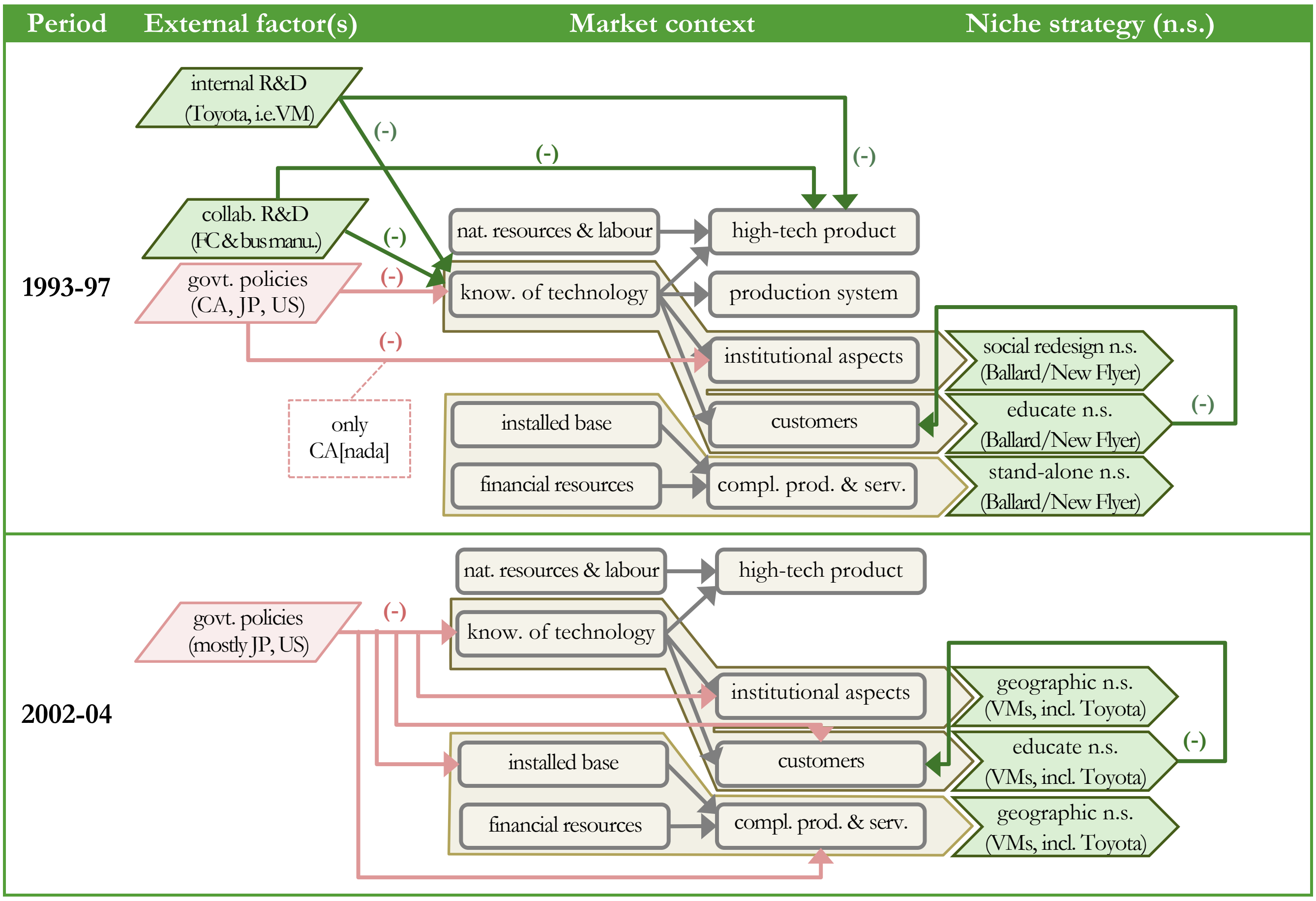
5.B From a market perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.

Both from a market and company perspective, the sequence of niche strategies can be described as an accumulation of efforts to circumvent the existing barriers to large-scale diffusion in the short-term, and remove these barriers in the long-term. To circumvent the price barrier, initially the 'top' niche strategy had been used; gradually the 'subsidized' and 'leasing' niche strategies were added. In absence of evidence that these efforts were planned and deliberate up-front, it is only possible to classify the logic as emergent.





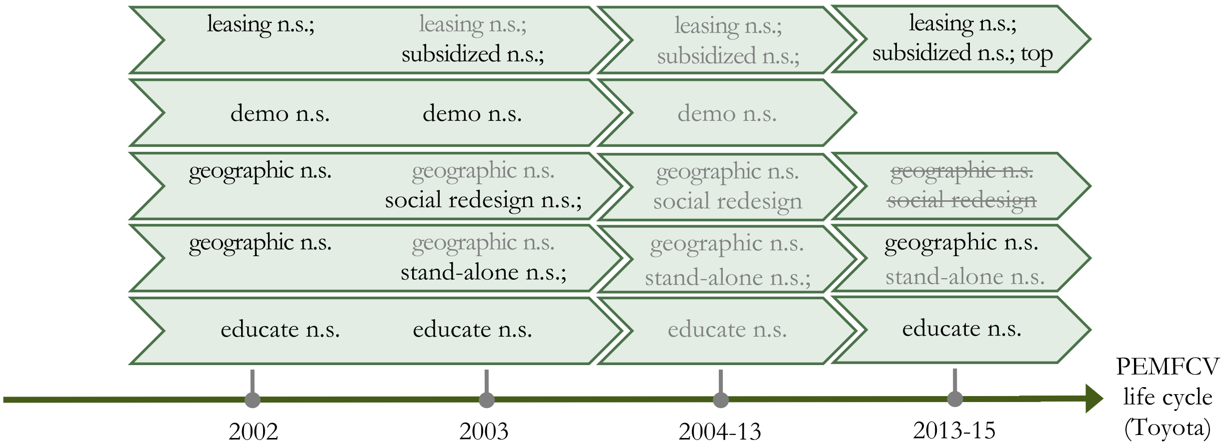
Another sequence which can be observed from a market-level perspective was aimed at increasing technological visibility. Despite the initial 'customers' barrier, the product could nonetheless be introduced via an application to which consumers would have exposure: public transport. This was made possible by incorporating the 'social redesign' niche strategy in the initial instance. The 'stand-alone' niche strategy is also critical to the initial instance of the sequence, since there was no available infrastructure to begin with. However, with the increased technology visibility, the first set of strategies could –partly– stimulate the development of a hydrogen refuelling infrastructure, which allows the introduction in a consumer market, in a limited geographical area. The subsequent introduction would yet again further the technology visibility, ultimately resulting in positive feedback loop. All of the former instances were doubled by the 'educate' niche strategy, which was in fact the active force in changing the lacking customer knowledge.



5.C From a company (incl. network of companies) perspective, describe –if any– the emergent/deliberate logic at the basis of the series of niche strategies.

The sequences of niche strategies are to be explored from the central actor perspective. Ballard, for instance, does not fit the role since it mainly provided fuel stacks for different automakers, rather than producing PEMFCVs.

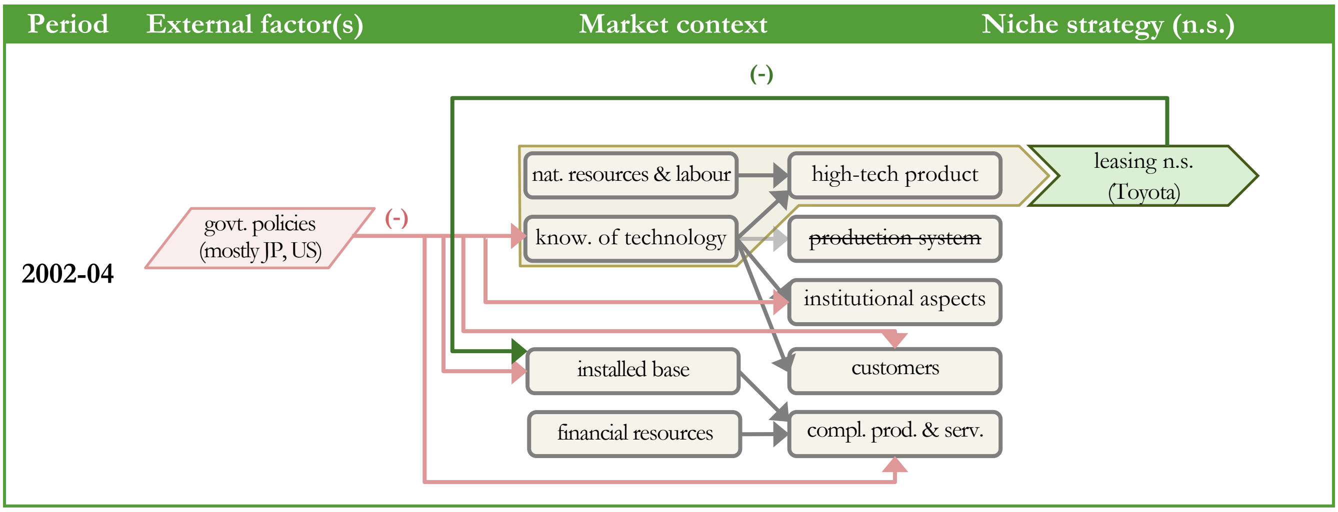
In fact, based on the case evidence, only the actions of Toyota can be looked upon from a company perspective. Figure 50 presents the chronology of niche strategies deployed by Toyota. In December 2002, Toyota began leasing PEMFCVs to corporate customers and governments, and in 2003 the FCHV-BUS2 was introduced in collaboration with Hino. Please note that according to the theory laid out in section 3.3.2 these niche strategies should be considered simultaneous since they occurred at more or less the same moment in time.

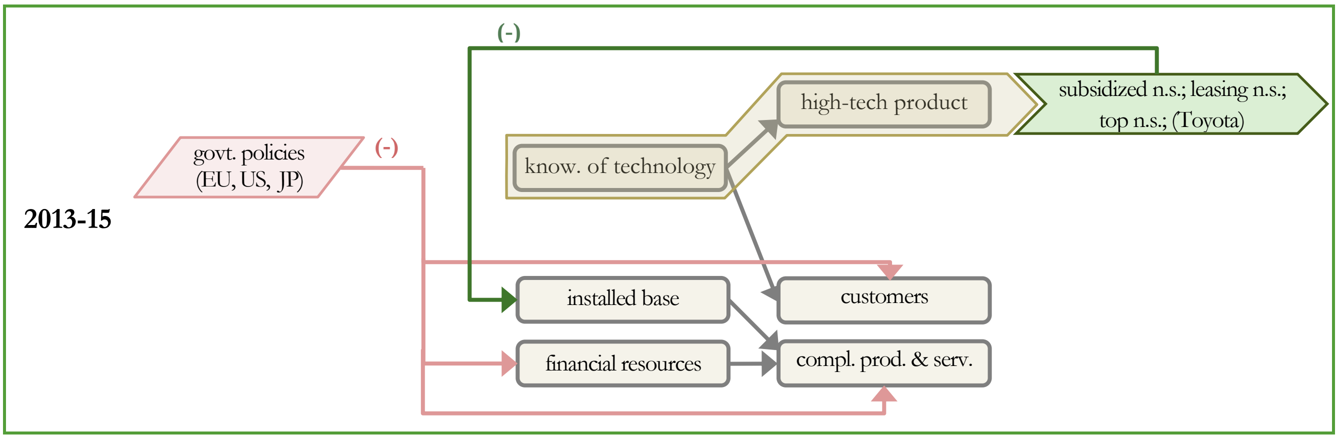


Legend:
See Figure 11

Figure 50: Chronology of niche strategies – PEMFCV technology – Toyota Motors

From the early 2000s, Toyota had its sights on a future commercial introduction (see Toyota Motors 2004), and can be considered to have used the deliberate sequence 'leasing' niche strategy –starting with 2002– followed by 'top' niche strategy in 2015, once the price barrier became less prohibitive. It should be noted that in 2015 the cost pressures are further depressed by the simultaneous use of a 'subsidized' niche strategy, which –for instance– in California accounts to about 10% of the vehicle's retail price.





By coupling the above product introductions with an 'educate and experiment' niche strategy, the vehicle manufacturer arguably strived to remove/diminish the magnitude of the 'customers' barrier.

5.D Why did a sequence of niche strategies – if any – emerge during the market adaptation phase?

Specifically in the automotive segment, the sequence of niche strategies appeared based on several rationales: (1) removal of barrier(s), (2) market skimming, (3) technology visibility, (4i) search for customer segments or (4ii) revenue diversifying efforts.

The removal of barriers can be seen from a deliberate logic perspective when looking at the overall sequence deployed by Toyota Motor. Both the prohibitive price aspect and the customer's knowledge of the technology were targeted.

The exact situation might also be regarded from a market skimming rationale, since (a) the initial vehicles were leased to corporations and government, rather than end consumers as in the later instance, thereby indicating a subtle shift in the customer segment and (b) a lower price point would have been likely commanded in 2015, as opposed to 2002. Point (a) was already confirmed via case evidence. Point (b) also holds true when comparing the non-inflation-adjusted cumulated 30-months lease from 2005 (see Toyota Motor 2005) –at interest rate YEN-USD from July 2005, i.e. 0.008931USD/YEN– with the 2015 retail price (see Toyota Motor Sales USA 2015). The calculation yields a difference of more than $200,000; that is even before adjusting for inflation for the 10-year difference. Therefore, based on the subtle shift in customer segment and the lower price point commanded from consumers, Toyota Motor is considered to have used a market skimming rationale, when deploying the sequence 'leasing' followed by 'top' niche strategy.

From a market perspective, the actors can be thought of to have increased the technology visibility via 'educate', 'stand-alone' and 'social redesign' niche strategy as a first instance in public transport buses. Then, automakers proceeded to the consumer market for passenger vehicles via the coupling of 'geographic' and 'educate' niche strategies. Given that there is no indication of a deliberate up-front scheduling of the different instances, the logic will be classified as emergent.

Several markets were being pursued for a customer segment in which diffusion would accelerate. Additionally, if looked from the substantial R&D costs the sequence of niche strategies can be seen to fulfil the goal of revenue diversifying efforts. Both aspects would fall under the cupola of exploration-based emergent logic.

Reflecting first on the search for a more befitting customer segment, the lack of available hydrogen infrastructure was the biggest hurdle to the diffusion of the product. From this perspective, the customer segments can be split in two groups: those that would allow dedicated refuelling stations, and those which would require a specific limited geographical area with a sufficiently developed infrastructure. The subsequent expansion from public transport, to passenger cars, and thereafter to materials' handling vehicles entailed an alternate succession of ‘stand-alone’ and ‘geographic’ niche strategy, in the search for customer segments where diffusion would accelerate at a faster rate.

Regarding the revenue diversifying efforts an explanation should be given as to why the sequence does not include any price-related niche strategies; for e.g. ‘top’ or ‘subsidized’. Note that by design niche strategies include the generation of revenue, therefore the inclusion of price and the volume supplied is not needed to conclude on the rationale. Furthermore, had a price-related strategy been introduced it would have commanded a say on the profitability of each segment or the willingness-to-pay; aspects which fall beyond the mere scope of revenue-generation. Hence, the sequence is sufficient to explain how manufacturers expanded across multiple customer segments with the help of niche strategies, in the effort to diversify their sources of revenue and depress the substantial R&D costs. Lastly, note that the situation cannot be illustrated by Toyota, since the company explored only two customers segments and both at more-or-less the same moment in time, rather than sequenced across the market adaptation phase.

5.E Based on which criteria did companies opt for a wait-and-see, niche or large-scale introduction strategy?

Based on the case evidence, we cannot conclude that companies made use of the wait-and-see or large-scale introduction strategies. The companies that did opt to introduce their products in strategic niches, did so because of the prohibitive barriers. In other words, managers who were willing and eager to enter the market could only do so via strategic niches. Under the business models and value propositions investigated, neither made practical sense on a large-scale.

5.3.6.CONCLUSION

6.A How do the case results contribute towards answering the research questions?

Table X is meant to summarize the outcomes of the case which contribute towards answering the research questions. The descriptions from the right hand-side column are an abridged versions of the conclusions presented in earlier sections.

Table X: Preliminary answer to research questions based on the PEMFCV case results

Research question	Preliminary answer
1.What is a good approach to explore sequences of niche strategies for the case of radically new high-tech products?	The methodology proposed under section 4.4 proved helpful, but not comprehensive enough for the investigation of sequences of niche strategies in this particular case. More specifically, the impact of a single niche strategy on the core or contextual factors could not be systematically identified. The core reason lies in the fact that the current methodology is less suited for complex cases when there are simultaneously many core factors, many contextual factors, many niche strategies and multiple external factors for an extended period of time. It simply does not provide an explicit and complete set of measures to identify –at least qualitatively; at best quantitatively– the above-cited impact.
2.How do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	For this particular disruptive case, the barriers to large-scale diffusion were present from the beginning of the market adaptation phase. All the barriers experienced a decrease –only– in magnitude throughout the specific time-period investigated. Among the remaining barriers until the end of the phase, the most influential one remained the lack of a hydrogen refuelling infrastructure, i.e. ‘complementary products’.

3.Why do barriers to large-scale diffusion change over the span of the market adaptation phase in the case of radically new high-tech products in the selected industry?	In conclusion, the change in the barriers to large-scale diffusion over the span of the market adaption phase can be explained by two aspects: (1) external factors; and (2) niche strategies. Combined, these factors resulted in the complete or partial removal of core and contextual factors.
4.Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?	There is no evidence towards why companies should opt for the wait-and-see or large-scale introduction strategies. The case proves that niche strategies offer managers with the option of introducing their products in the market, when there are prohibitive barriers to large-scale diffusion. This finding supports earlier claims by Ortt et al. (2013). Niche strategies can also be used to ramp up the volume, such that economies of scale can be achieved.
5.What could be the logic and rationale behind sequences of niche strategies for market creation?	For the case of the PEMFCV technology, there are several main rationales: (1) removal of barrier(s), (2) market skimming, (3) technology visibility, (4i) search for customer segments or (4ii) revenue diversifying efforts.
6.What are logical sequences of niche strategies in the selected industry?	This particular case illustrates at least three logical sequences. Firstly, 'leasing' niche strategy followed by 'top' niche strategy can allow automakers to initially experiment with the technology in the space of a realistic user experience while mitigating the prohibitive high-price, and thereafter use this experience in the subsequent commercial introduction; also for a lower price point. Specifically for technologies with societal benefits, government policies can allow for 'subsidized' niche strategy to further depress consumer cost pressures. This situation was illustrated in the case of Toyota Motor between 2002 and 2015. Secondly, by simultaneously using 'educate', 'stand-alone' and 'social redesign' niche strategies in the area of public transport vehicles, followed by the coupling of 'geographic' and 'educate' niche strategy in a consumer market, automakers can later on leverage the increased availability of a hydrogen refuelling infrastructure which –partly– resulted from the increased technology visibility in the specific geographical areas. This would yet again further the technology visibility. Note that by using 'social redesign' niche strategy as part of the initial sequence, yet still introducing the technology where consumers would experiment with it –i.e. public buses– the technology visibility was possible in the first place. Thirdly, for the search for customer segments in the context of a lacking hydrogen refuelling infrastructure, the alternate sequence of 'stand-alone' niche strategy, followed / preceded by 'geographic' niche strategy was used. The example was seen in succession from public transport buses to passenger vehicles to materials handling vehicles. The same sequence applies for the revenue diversifying efforts, as explained under section 5.3.5.

This final case on the PEMFCV technology offered a last set of interesting insights and reflection points towards answering the research questions, and suggestions for further investigations; for e.g. developing a more comprehensive methodology for the precise assessment of the impact of every individual niche strategy on the core and contextual factors.

6.B What are the theoretical implications of the case results?

The conceptual model presented in section 3.2 is partially supported by the PEMFCV case. The key difference lies in the fact that neither the external factors, nor the niche strategies influenced the creation of (new) barriers. They did however prove instrumental in gradually decreasing the magnitude of three of the core factors, and completely removing two, as shown by the dark green and light red arrows from Figure 51.

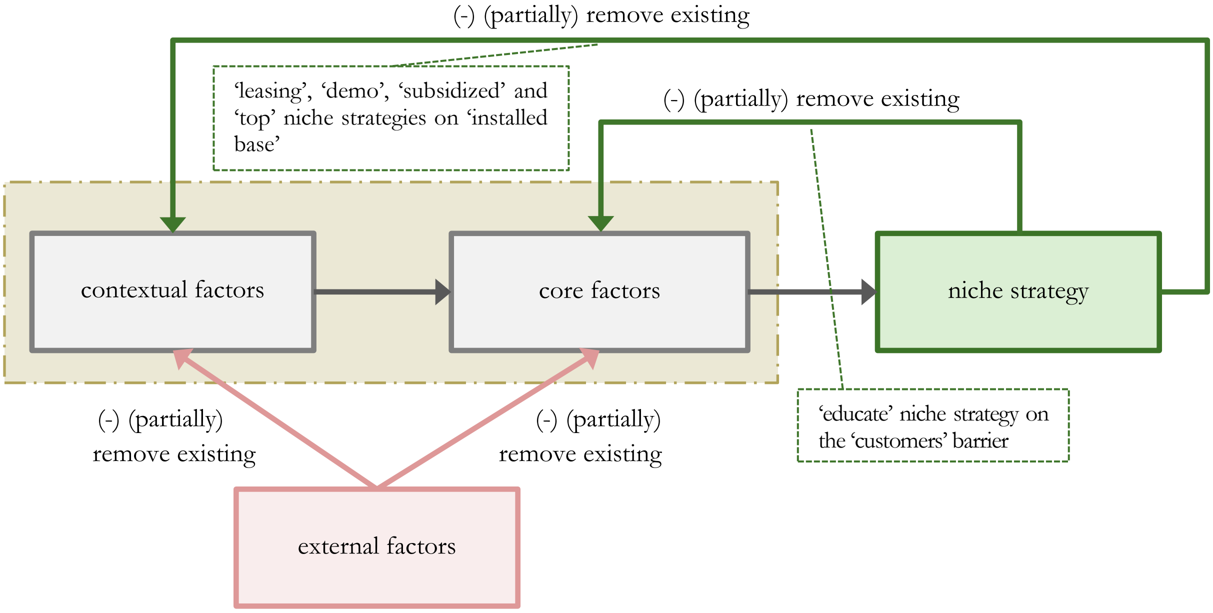


Figure 51: Conceptual model – PEMFCV technology

The case proved instrumental in uncovering a new niche strategy: leasing. In order to circumvent the prohibitive price of ownership of a PEMFCV, the automakers leased the vehicles to selected customers, rather than selling them for their full ownership price. The leasing niche strategy represents an alternative solution to overcoming the cost barriers of radically new high-tech products in the automotive industry.

A new contextual factor was uncovered: installed base. The concept is well documented in the management literature. As Katz & Shapiro (1985, p.424) note "[p]ositive consumption externalities arise for a durable good when the quality and availability of postpurchase service for the good depend on the experience and size of the service network, which may in turn vary with the number of units of the good that have been sold." For the PEMFCV case, installed base refers to the number of available vehicles on the market that would require a hydrogen refuelling infrastructure.

The proposal is to incorporate 'installed base' as a new contextual factors. Firstly, a short elaboration is required as to why it is not a core factor. Remember that contextual factors represent the reason for the emergence of barriers. For the PEMFCV case, the relatively low number of hydrogen vehicles on the market –i.e. the reason– prevented the large-scale development of the refuelling infrastructure –i.e. the barrier. Thus, 'installed base' befits more to the role of contextual factor, than that of core. Secondly, it should be argued why it cannot be included in the available list of factors, as was the case for financial resources. The reason is that the concept fundamentally departs from the currently available ones –from the list of Ortt et al. (2013)– and would therefore be impractical to coupled it with another factor.

Lastly, the newly identified contextual factor of 'financial resources' was also present, and had impacted the availability of 'complementary products and services'. Recommendations as to how to incorporate this factor will be made under sub-section 10.1.4.

6.C What are the managerial implications of the case results?

The status of the barriers can influence the company's decision to exit the business: Prater (1990) referred to the high cost of the membrane and that of the platinum loading –as compared to the competing PAFC technology at the time– as one of the decision drivers behind GE's withdrawal from a potential commercial market for PEMFC in in the early 1980s.

A second managerial implication is that technology visibility can be achieved via sequences of niche strategies not necessarily in consumer markets. Public transport buses are not consumer products, but they are visible to the mass market.

6. CROSS-CASE ANALYSIS

The purpose of this chapter is to compare the results of the three cases. The synthesis will serve as the primary input for addressing chapters 7, 8, and 9.

6.1. CASE DIVERSITY

Table XI reports on the observed values for the four selection criteria formulated under section 4.5: (1) length of the adaptation phase, (2) number of central actors active during the time period investigated, (3) how critical is the technology to the automobile, and (4) how disruptive was the technology to the system around automobiles. Except for the exact length of the adaptation phase and the number of central actors, the remainder of the values were known before the actual completion of the cases.

Table XI: Case diversity

	DCT	ABS	PEMFCV
adaptation phase	21 years	33-37 years	–
no. of central actors	1-2	6	6+
criticalness of func.	critical	secondary	critical
disruptiveness	non-disruptive	non-disruptive	disruptive

As observed there is variation in the length of the adaptation phase. In fact, the phases were all sufficiently long to account for multiple niche strategies to emerge.

Except for the 'knowledge of application' all the other contextual and core factors were observed during the different market contexts of the three technologies. Not all niche strategies were employed by the market actors. Among the non-observed ones are: 'hybridization', 'lead user' and 'explore multiple markets' niche strategies.

6.2. CHANGE IN THE BARRIERS TO LARGE-SCALE DIFFUSION

6.2.1. HOW DID THE BARRIERS TO LARGE-SCALE DIFFUSION CHANGE OVER THE SPAN OF THE MARKET ADAPTATION PHASE?

According to the classification of core factors laid out in section 2.4.2, there can be technological factors and social factors. Consequently, two sub-chapters will follow exploring the change in the barriers for these two particular categories.

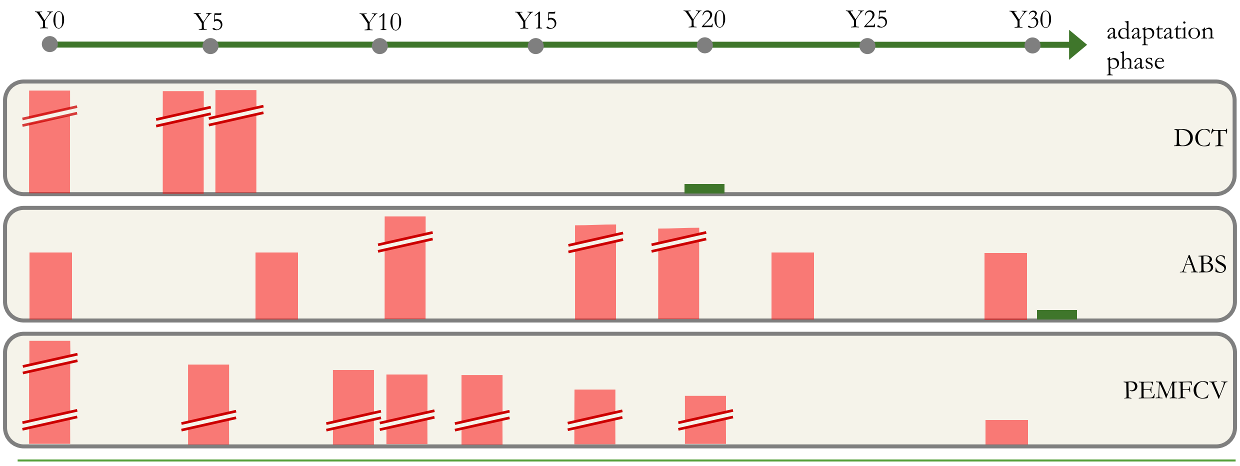
TECHNOLOGICAL BARRIERS

Under technological barriers there are three corresponding core factors: new high-tech product, production system, and complementary products and services. Each of these will be addressed in the following three sections. Lastly, the outcomes will be aggregated one level up, i.e. they will be related to the higher concept of technological barriers.

NEW HIGH-TECH PRODUCT

The first observation to be made from Figure 52 is that the 'new high-tech product' factor hampered diffusion in all three cases. Furthermore, across the cases it consistently continued to impact diffusion throughout the period of the market adaption phase which was investigated; an exception might be the DCT case where the factor had disappeared one year before the last remaining factor.

Secondly, qualitatively speaking the rate at which the magnitude decreased across all cases is not consistent. For instance, whereas in the PEMFCV case there can be observed a gradual decrease, in the ABS case mid-way in the market adaptation phase the magnitude of the factor increased when the shift from mechanical to electronic ABS occurred. Hence, the implication is that the 'new high-tech product' factor need not necessarily decrease in magnitude over time due to the accumulation of relevant knowledge, as one would generally expect.



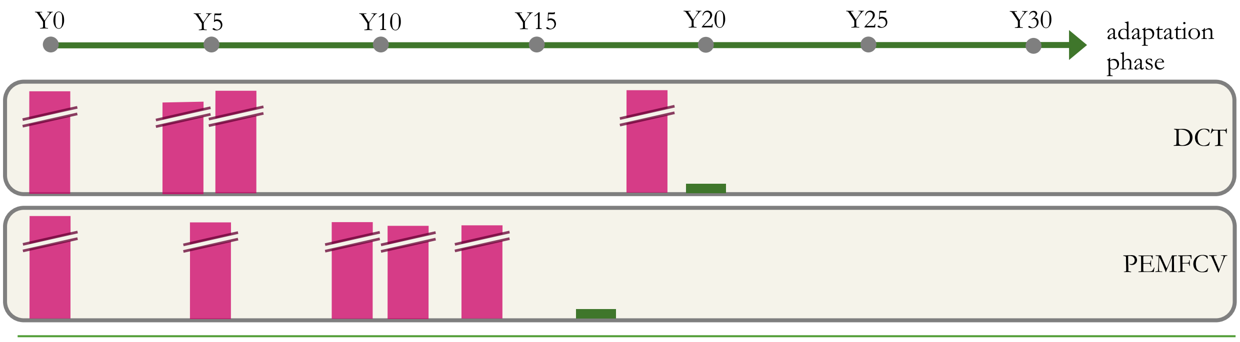
Legend:
See Figure 12

Figure 52: Cross-case comparison of the dynamics of the 'new high-tech product' core factor

PRODUCTION SYSTEM

The production system hampered diffusion in only the DCT and PEMFCV cases. Hence, Figure 53 makes reference only to these two cases.

The first insight from the dynamics is that the barrier need not necessarily decrease. For instance, when Porsche scrapped all the special tools for manufacturing of the 969 model, the availability of production systems decreased. This can be generalized to any case where production facilities are being decommissioned.



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See Figure 12

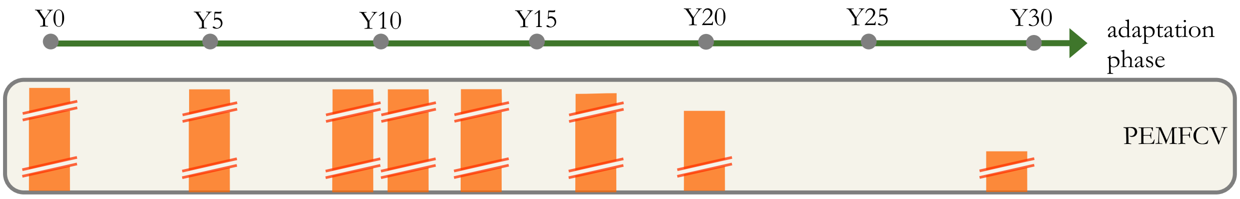
Figure 53: Cross-case comparison of the dynamics of the 'production system' core factor

Secondly, it can be observed that although available mass-production facilities may be available, the diffusion need not necessarily take off. Generically speaking the reason could be that manufacturers do not supply at full capacity

–take for instance the introduction in sport cars by Volkswagen– or that the market demand for the product undercuts significantly the available supply –as inferred from the PEMFCV case.

COMPLEMENTARY PRODUCTS & SERVICES

Complementary products and services were blocking diffusion only for the PEMFC vehicle. As testimony to the disruptive nature of the product, the barrier not only remained active up until the moment of writing, but among the other barriers active in the PEMFCV case it was arguably the biggest hurdle to large-scale diffusion.



Legend:
See Figure 12

Figure 54: Cross-case comparison of the dynamics of the 'complementary products & services' core factor

Refuelling stations can be decommissioned and the overall available supply would decrease as a result. For instance, had the technology promise diminished drastically over time, this effect might have been observed since there was no market incentive for infrastructure actors to provide these services or products. In that case, the barrier would not have only decreased in magnitude.

SYNTHESIS

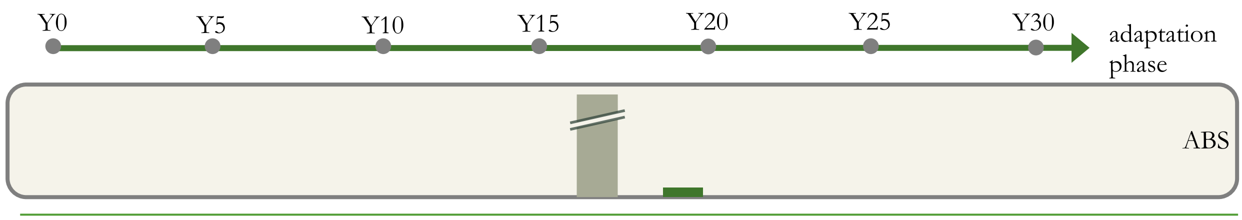
If a technological barrier were to hamper diffusion, then it correlated with the barrier being observed from the very beginning of the market adaptation phase. Towards the very end of the phase they generally tended to evaporate, but that was not common to all technologies–see ABS for instance. Lastly, these barriers need not necessarily decrease in magnitude with the accumulation of knowledge, time or physical resources.

SOCIAL BARRIERS

There are three social core factors: suppliers, customers and institutional aspects. Each of these will be addressed in the following three sections. Lastly, the outcomes will be aggregated one level up, i.e. they will be related to the higher concept of social barriers.

SUPPLIERS

The 'suppliers' core factor was observed in only one case. The time span during which it hampered diffusion was relatively short, and occurred with the shift from mechanical ABS to electronic ABS.

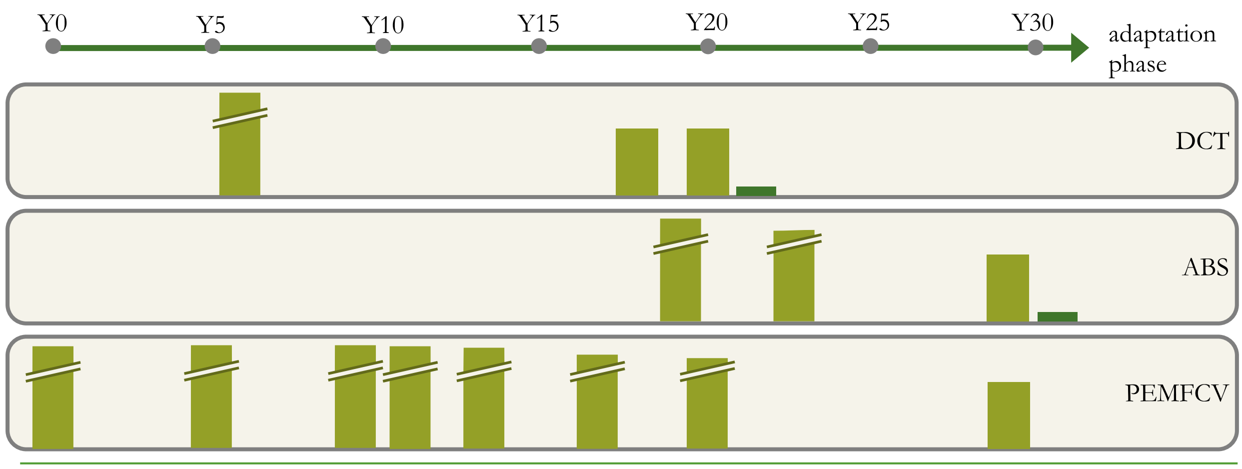


Legend:
See Figure 12

Figure 55: Cross-case comparison of the dynamics of the 'suppliers' core factor

CUSTOMERS

Conversely to the previous one, the 'customers' factor was found to hamper diffusion in all three cases, as shown in Figure 56. Across all these case it was repeatedly prevalent up until the very end, as one of the last barriers to disappear. Secondly, qualitatively speaking, it tended to decrease in magnitude over the market adaptation phase.



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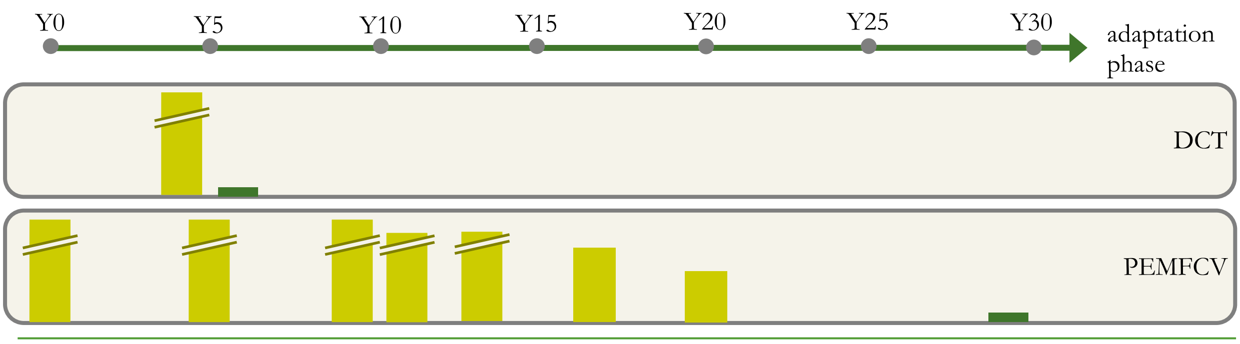
See Figure 12

Figure 56: Cross-case comparison of the dynamics of the 'customers' core factor

INSTITUTIONAL ASPECTS

The two cases where this barrier appeared are in fact very much different from one another. The regulatory hurdle in the DCT case was exclusively materialized in the racing market, whereas for the PEMFCV case institutional aspects had hampered diffusion in the consumer market.

These barriers need not necessarily decrease over time. In response to the technology introduction, new regulation can appear which can stifle diffusion in a particular market. Conversely, in the PEMFCV case the increased technology introduction was –on an aggregate level– positively correlated with the diminishing of institutional barriers.



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See Figure 12

Figure 57: Cross-case comparison of the dynamics of the 'institutional aspects' core factor

SYNTHESIS

The dynamics of the observed social factors was quite different from case to case. In some situations, these factors were very much of a sporadic nature, whereas in others they continued to hamper diffusion from start to end.

6.2.2.WHY DID THE BARRIERS TO LARGE-SCALE DIFFUSION CHANGE OVER THE MARKET ADAPTATION PHASE?

Aggregately, the change in the barriers was explained by three drivers: (1) external factors; (2) niche strategies; and (3) the change from one market to another; for e.g. from racing to a consumer market or from aviation to automotive. Table XII breaks down –per driver– the specific influence on the magnitude of the core and/or contextual factors.

Table XII: Cross-case comparison of the influence of the three change drivers on the core or contextual factors

		Case: DCT		Case: ABS		Case: PEMFCV	
		contextual factors	core factors	contextual factors	core factors	contextual factors	core factors
(1) external factors	diminish:	supported	supported	supported	supported	supported	supported
	increase:	supported	unobserved	supported	unobserved	unobserved	unobserved
(2) niche strategies	diminish:	unobserved	supported	supported	supported	supported	supported
	increase:	supported	supported	supported	supported	unobserved	unobserved
(3) change markets	diminish:	supported	supported	unobserved	unobserved	unobserved	unobserved
	increase:	unobserved	unobserved	supported	supported	unobserved	unobserved

Firstly, across each case the influence of external factors and that of niche strategies in diminishing the magnitude of the factors was –with only one exception– consistently supported.

Secondly, based on Table XII, it can be concluded that the hypothesized influence of niche strategies on the core and contextual factors posited in section 3.2 is supported. More so, niche strategies were also proven to increase the magnitude of the factors. The observation is important, since the reviewed literature had formerly neglected the impact. This will be discussed at length under chapter 10.

The above findings form the input for section 10.1.1 Conceptual model. Aggregated across all cases, the influence of all three change drivers is supported.

Table XIII and Table XIV summarize the influence of the different external factors and niche strategies on the six core factors.

Table XIII: Cross-case comparison of the influence of external factors and niche strategies on the core factors – Part 1/2

		new high-tech product	production system	complementary products & services
(1) external factors	diminish:	internal R&D (DCT, ABS, FCV); demonstrations (FCV)	internal R&D (DCT)	government policies (FCV)
	increase:			
(2) niche strategies	diminish:	tech. redesign n.s. (ABS); top n.s. (ABS)		
	increase:			

Table XIV: Cross-case comparison of the influence of external factors and niche strategies on the core factors – Part 2/2

		suppliers	customers	institutional aspects
(1) external factors	diminish:		demonstrations (FCV); government policies (FCV)	lobbying (ABS); government policies (FCV)
	increase:			
(2) niche strategies	diminish:		educate n.s. (DCT, FCV)	
	increase:		tech. redesign n.s. (ABS); top n.s. (ABS)	demo n.s. (DCT);

Table XV and Table XVI summarize the influence of the different external factors and niche strategies on the contextual factors. The reader is advised to note that 'knowledge of application' is not listed, since the factor was not encountered during the case research.

Table XV: Cross-case comparison of the influence of external factors and niche strategies on the contextual factors – Part 1/2

		knowledge of technology	natural resources, labour and capital	socio-cultural aspects
(1) external factors	diminish:	external R&D (DCT, ABS, FCV); internal R&D (DCT, ABS, FCV); collaborative R&D (FCV); government policies (FCV); demonstrations (FCV)	government policies (FCV)	
	increase:			
(2) niche strategies	diminish:	tech. redesign n.s. (ABS); top n.s. (ABS)		
	increase:			

Table XVI: Cross-case comparison of the influence of external factors and niche strategies on the contextual factors – Part 2/2

		macro-economic aspects	accidents or events	installed base
(1) external factors	diminish:			government policies (FCV)
	increase:	economic downturn (DCT)		
(2) niche strategies	diminish:			demo n.s. (FCV); leasing n.s. (FCV); subsidized n.s. (FCV); top n.s. (FCV)
	increase:		demo n.s.(DCT); tech. redesign n.s. (ABS); top n.s. (ABS)	

6.3. OPTING BETWEEN WAIT-AND-SEE, NICHE OR LARGE-SCALE INTRODUCTION STRATEGY

Table XVII summarizes the information from Table VIII, Table IX, and Table X pertaining to the 4th research question, i.e. "Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?"

Table XVII: Drivers for opting between a wait-and-see, niche or large-scale introduction strategy

	DCT	ABS	PEMFCV
wait-and-see	not observed	when the product could be developed and barriers could be removed without necessarily introducing it in the market	not observed
niche	when barriers continued to hamper diffusion	when barriers continued to hamper diffusion	when it is essential to build up economies of scale for large-scale introduction; and/or when barriers continued to hamper diffusion;
large-scale introduction	once barriers stopped hampering diffusion		not observed

The outcomes for niche and large-scale introduction are in line with the logic proposed by Ortt et al. (2013). There were also two additional insights. The first is that niche strategies were used when the gradual ramp-up of production was essential in lowering down the manufacturing costs of PEMFCVs, primarily that of the fuel cell. This is particularly the case when large-scale introduction is critically dependent on economies of scale.

The second insight is how the wait-and-see strategy can be used in parallel with product development and changing market context. Bosch continued to develop the ABS system, while in the same time leveraging the positive changes on the market context –i.e. barriers decreased in magnitude due to other actors– and also proactively influencing the barriers via press demonstration or other such means.

6.4. SEQUENCE OF NICHE STRATEGIES

6.4.1. WHY DID A SEQUENCE OF NICHE STRATEGIES – IF ANY – EMERGE DURING THE MARKET ADAPTATION PHASE?

Table XVIII aggregates the answers from Table VIII, Table IX, Table X pertaining to the final, i.e. "What are logical sequences of niche strategies in the selected industry?" The typology from section 3.3.2 is used, as shown by the two left hand-side column which distinguishes between emergent or deliberate sequences; and one level deeper between an exploitation rationale and an exploration rationale.

The explanations of each bullet point from Table XVIII can be found in an abridged version under Table VIII, Table IX, and Table X. The purpose of this sub-section is not to re-iterate those concrete examples, but rather form the basis for the conclusions under section 9.1.

Table XVIII: Reasons for the emergence of sequences of niche strategies

		DCT	ABS	PEMFCV
emergent	exploitation, based on:	• changing market context	• diminish of barrier(s); in this case 'new high-tech product' • competitive response	• technology visibility
emergent	exploration, based on:	–	• search for customer segments	• search for customer segments / revenue diversifying efforts
deliberate	exploitation, based on:	–	• market skimming	• removal of barrier(s) • market skimming
deliberate	exploration, based on:	–	–	–

Case examples for emergent and deliberate sequences of niche strategies were found. Furthermore, by categorizing these examples under the exploitation-exploration continuum, it can be observed there are three generic types of sequences: (1) exploitation- or (2) exploration-oriented emergent ones, and (3) exploitation-oriented deliberate ones. There was no evidence of an exploration-oriented deliberate sequence, an outcome which may be explained by two aspects: either the situation is indeed conceptually conceivable, but factually unrealistic as posited under section 3.3.2, or this early presumption materialized as a research bias therefore making it less likely to uncover such examples which would hint that the necessary measures for reliability were not sufficient.

6.4.2. WHAT ARE LOGICAL SEQUENCES OF NICHE STRATEGIES IN THE SELECTED INDUSTRY?

The answers under the current section are grouped according to the typology presented under section 3.3.2, and explored under 6.4.1: (1) exploitation-oriented emergent sequences, (2) exploration-oriented emergent sequences, (3) exploitation-oriented deliberate sequences, and (4) exploration-oriented deliberate sequences. This sections draws on insights from Table VIII, Table IX, and Table X, specifically pertaining to the summarized answers for the 6th research question.

EXPLOITATION-ORIENTED EMERGENT SEQUENCES OF NICHE STRATEGIES

Under this particular typology of logic there were four reasons uncovered for why sequences of niche strategies emerged: changing market context, competitive response, diminish magnitude of barrier(s), and technology visibility.

CHANGING MARKET CONTEXT

The sequence 'demo, experiment and develop', followed by 'educate' and 'geographic' niche strategy was observed. The example stems from the DCT case, as deployed by Volkswagen AG.

COMPETITIVE RESPONSE

The observed sequence was 'top' niche strategy, followed by 'technological redesign'. Ford decided to experiment with ABS systems after Jensen's FF introduction, and the aforementioned sequence was resulted.

DIMINISH MAGNITUDE OF BARRIER(S)

In the ABS case, in targeting the 'new high-tech product' barrier, simultaneously 'technological redesign' and 'top' were used, followed the former instance once again. Using this sequence, OEMs and automakers lowered the complexity and costs of secondary components, i.e. decrease the magnitude of the 'new-high tech product' barrier.

TECHNOLOGY VISIBILITY

The observed sequence was the simultaneous use of 'educate', 'stand-alone' and 'social redesign' niche strategies in the area of public transport vehicles, followed by the coupling of 'geographic' and 'educate' niche strategy.

EXPLORATION-ORIENTED EMERGENT SEQUENCES OF NICHE STRATEGIES

Under this particular typology of logic there were two reasons uncovered for why sequences emerged: search for customer segments and revenue diversifying efforts.

SEARCH FOR CUSTOMER SEGEMENTS

The observed sequence was 'stand-alone' niche strategy, followed / preceded by 'geographic' niche strategy. The example was illustrated in the PEMFCV case, where from a market perspective actors could alternate the succession of the two strategies in finding other customer segments more eager to adopt the product, and therefore accelerate diffusion.

It may appear counter-intuitive that the 'customers' barrier was not targeted a niche strategy in the observed sequence. Although 'educate and experiment' was used by actors in the case, please note that such a strategy targeted alleviating the customer barrier. In this sense it would have not have helped towards the goal of exploring those segments where product introduction would be possible.

Another observed sequence for the same search of customer segments was 'top' niche strategy coupled with 'technological redesign', followed yet again the former couple. This was employed by Dunlop, when the company expanded from providing ABS units in aircrafts to automotive: passenger vehicles and trucks. However, since this sequence did not take place exclusively within the automotive market, it did not contribute directly towards answering the research question.

REVENUE DIVERSIFYING EFFORTS

For revenue diversifying efforts the same sequence as in the earlier PEMFCV case was used, with the additional key point that substantial R&D costs were involved in the development of the product, therefore commanding this rationale. For brevity, the sequence will not be repeated.

EXPLOITATION-ORIENTED DELIBERATE SEQUENCES OF NICHE STRATEGIES

Under this particular typology of logic there were two reasons uncovered for why sequences of niche strategies emerged: market skimming and removal of barriers.

MARKET SKIMMING

The sequence 'leasing' followed by 'top' niche strategy was observed. The example stems from the PEMFCV case. Toyota used it to subsequently command a lower price point from subtle differences in the customer segments: firstly corporate and government clients, and thereafter the consumer market.

Towards the same goal, but not observed exclusively within the automotive market was another sequence: 'top' followed by 'top' niche strategy. Dunlop used it to expand from aviation to automotive, when introducing the electronic version of ABS.

REMOVAL OF BARRIER(S)

The overall sequence used by Toyota Motor between 2002 and 2015 was targeted at the removal of barriers, specifically: prohibitive price barrier and educating customers. Further investigation can reveal which individual strategies targeted which barriers. For the time being, the impact of each individual strategy or its role could not be distinguished based on the case evidence. Given this fact, the sequence will not be presented here as it is not yet clear which niche strategy played a role towards meeting the goal –i.e. removal of barriers– and which not.

7. BARRIERS TO LARGE-SCALE DIFFUSION

This chapter is divided into two sections: 7.1 answers research question no. 2; and 7.2 respectively no. 3. The conclusions are derived from section 6.2.

7.1. HOW DO BARRIERS TO LARGE-SCALE DIFFUSION CHANGE OVER THE SPAN OF THE MARKET ADAPTATION PHASE IN THE CASE OF RADICALLY NEW HIGH-TECH PRODUCTS IN THE SELECTED INDUSTRY?

The status and relative magnitude of the barriers to large-scale diffusion tended vary across cases. Thus, at an aggregate level there was no observed consistent pattern in terms of their dynamics. One might expect that there would be fewer barriers towards the end of the market adaptation phase, than in any earlier time periods. This is not necessarily true, as proven in the ABS case. Another generic conclusion on the dynamics of the barriers is that they need not necessarily taper off in magnitude during the span of the market adaptation phase.

Every case elicited a mix of both social and technological barriers, hinting at the importance of both aspects being considered when assessing the market context, and not only.

At the end of the market adaptation phase –and correspondingly at the start of market stabilization– there were no barriers to large-scale diffusion. This finding supports the existing literature on the pattern of development and diffusion by Ortt & Schoormans (2004).

Barriers need not necessarily decrease over time; they may also increase. Two generic mechanisms can explain the increase: (I) the requirements from the barrier –e.g. performance of 'new high-tech product' or the willingness-to-pay of 'customers'– can increase as a result of a market shift, therefore increasing the gap between the level at which the barrier would evaporate and the current state; or (II) the rate at which infrastructure or production assets are decommissioned exceeds the rate of which new ones are built/added.

7.1.1.TECHNOLOGICAL BARRIERS

When segmented down to technological and social barriers, some patterns begin to emerge. Firstly, on the topic of technological barriers, there are a couple of interesting observations: (1) If a technological barrier were to hamper diffusion, then it correlated with the barrier being observed from the very beginning of the market adaptation phase. (2) These barriers need not necessarily decrease in magnitude with the accumulation of knowledge, time or physical resources.

Combining the two insights, it means that the technological barrier(s) observed at the start of the market adaption phase –whether it's the 'new high-tech product', 'production system', or 'complementary products & services'– it can generally be expected to remain the only technological barriers hampering diffusion throughout the market adaptation phase. Although new technological barriers do not appear spontaneously mid-way through the phase, the existing ones can be expected to increase in magnitude and stifle diffusion even more than at the very start.

Segmenting further to the specific barrier level, there were observations made for each of the six core factors. In summary, the 'new high-tech product' factor hampered diffusion in all three cases, with no exception. This would entail that sequences of niche strategies take this factor into account when planning for the market context.

The availability of a 'production system' does not entail the end of the market adaptation phase. Despite the potential mass-production rate, two scenarios can still potentially occur: an over-supply relative to the market demand, or a deliberate under-supply by the manufacturer regardless of the market demand.

Central actors can deliberately build production capacities larger than the market demand (see Behling 2013b), although this meant operating on loss, in order to benefit from economies of scale. An executive of Toyota Motor Company sums it all up as: "[f]or cutting costs, technological innovation is important but mass production is effective" (Kyodo 2014).

'Complementary products and services' were consistently the biggest hurdle to large-scale diffusion in the disruptive case of the PEMFCV. This highlights the importance of considering such a case as part of the limited sample investigated.

7.1.2.SOCIAL BARRIERS

With respect to social barriers, the dynamics was very much case dependent. In some situations they elicited more of a sporadic nature, i.e. appearing spontaneously during the market adaptation phase or even disappearing just as fast. In other situations they were an impeding factor from start to end of the investigated time period.

The implication is that it is harder to plan a deliberate sequence of niche strategies that would account for any sporadic appearance of the social barriers. This correlates with the fact that no deliberate strategies were observed to include time periods during which societal barriers appeared spontaneously. In other words, any deliberate sequences that were observed were outside these uncertainty-prone periods.

Down at the specific barrier level, 'suppliers' core factor was only observed in the ABS case. It occurred with the shift from mechanical ABS to electronic ABS, and was active for a relatively short period of time; in the order of several years.

Conversely, the 'customers' barrier was observed for each of the three cases; hinting at the importance of this core factor relative to the others. From a qualitative stand-point it tended to decrease in magnitude quite abruptly at the end of the market adaptation phase, but this might only be obvious in hindsight.

Lastly, the 'institutional aspects' were observed both in the context of a consumer-market and a non-consumer one such as racing. The mere introduction of the technology can lead to opposing effects: in one instance it provoked the creation of institutional barriers, whereas in the other it was positively correlated with their decrease.

7.1.3.SYNTHESIS

In conclusion, the dynamics of the barriers was to a large degree case dependent. The immediate implication is that, as expected, the market context for radically new technologies has an uncertainty dimension. However, as sub-chapter 7.2 will detail, there are some factors which can influence the barriers, and therefore function as means for impacting the market context.

7.2. WHY DO BARRIERS TO LARGE-SCALE DIFFUSION CHANGE OVER THE SPAN OF THE MARKET ADAPTATION PHASE IN THE CASE OF RADICALLY NEW HIGH-TECH PRODUCTS IN THE SELECTED INDUSTRY?

The current section will report on the findings concerning the change drivers for the barriers; additionally, contextual factors will be also addressed herewith. The early general conclusions will be segmented down to the impact of the different drivers.

7.2.1.CHANGE DRIVERS

The change in the barriers to large-scale diffusion over the span of the market adaption phase can be explained by three aspects: (1) niche strategies, (2) external factors, and (3) change from one market to another. Figure 58 visualizes the impact of these factors on the barriers.

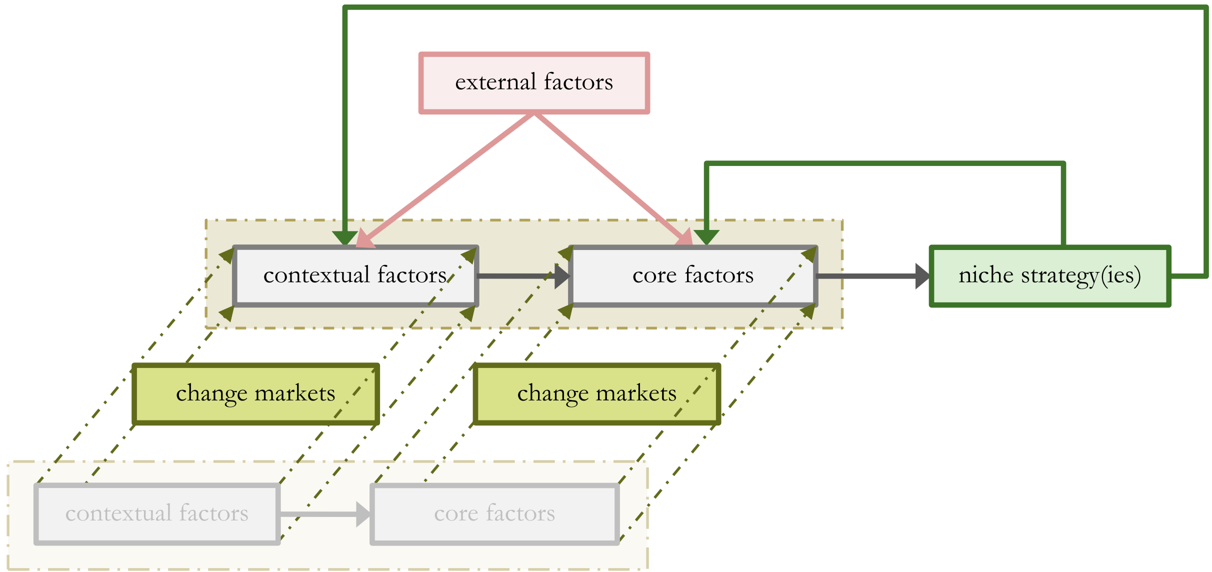


Figure 58: Factors impacting barriers to large-scale diffusion

The 'suppliers' core factor and 'socio-cultural aspects' contextual factor were not impacted by any of the change drivers. One explanation may be that they are slow to change or cannot be easily influenced. However, based on the case evidence this conclusion would not be easily supported, since the 'suppliers' barrier was only active for a couple of years, and the 'socio-cultural aspects' could only be investigated for a fairly similar period of time.

Nevertheless, some barriers are more often than not influenced by the change drivers. These are: 'new high-tech product' and 'customers'. An interesting observation is that these same barriers were found –see section 7.1– to be most prevalent across the three cases. This means that although they are typically hampering diffusion, the different array of change drivers can be used to diminish their magnitude.

7.2.2.NICHE STRATEGIES

Niche strategies varied in their degree of influence on the barriers from case to case, but also from niche strategy to niche strategy. However, not all strategies have an impact. The only ones which were observed to have an effect are as follows: 'demo, experiment & develop', 'top', 'subsidized', 'leasing', 'technological redesign' and 'educate (and experiment)' niche strategies. Among these, 'educate', 'subsidized' and 'leasing' were the single ones observed to only (partly) remove the factors; whereas the impact of the others was two-fold.

In fact, one of the most interesting findings is the significant number of situations when niche strategies were found to increase the magnitude of core or contextual factors; especially when considering that the literature on the topic had eluded this impact. The immediate implication is that niche strategy should be used with caution, since they can negatively affect the market context.

The effectiveness of 'leasing' or 'subsidized' niche strategies in removing factors is very limited, since they were only observed to diminish the magnitude of 'installed base', by releasing on the market vehicles that would require an available hydrogen refuelling infrastructure.

‘Educate’ niche strategy on the other hand had proven very useful, since (a) it helped diminish the prevalent –across all cases– ‘customers’ barrier, and (b) its impact was consistent in only one direction: (partly) remove the respective core factor.

The lack of impact of ‘demo’ on the contextual factor ‘knowledge of technology’ was surprising. The objective of the strategy is to improve upon it, but in the limited number of situations where ‘demo’ had been used, the advancements were not directly stemming from it, and therefore they were grouped under the external factor ‘internal R&D’.

‘Technological redesign’ and ‘top’ niche strategies are two-edged swords: they can prove effective in advancing the knowledge of the technology and improving product performance and costs, but they may easily deter diffusion either by creating institutional hurdles or by increasing the ‘customers’ barrier.

There are a multitude of core and contextual factors that were not influenced at all by niche strategies, as follows: ‘production system’, ‘complementary products and services’, ‘suppliers’, ‘natural resources, labour and capital’, ‘socio-cultural aspects’, and ‘macro-economic aspects’. This raises the observation whether these factors cannot be influenced by niche strategies.

While for some factors it would be hard to conclude or even posit in one way or another, for ‘production system’, ‘complementary products and services’, and ‘natural resources, labour and capital’ neither of the wide array of niche strategies deployed during the extensive market adaptation phase for the PEMFCV case had any influence. At best, some had an indirect influence; for e.g. by increasing the number of vehicles on the market and therefore decreasing the magnitude of the ‘installed base’, the hydrogen infrastructure was offered a stimulus for growth Thus, for these three factors it is posited that niche strategies can do little to influence them directly. Luckily for managers, external factors can influence them, as presented during the next section.

Technological barriers were not observed to increase as a result of the influence of niche strategies. Conversely, the number of niche strategies that were found to increase the magnitude of the social barriers was larger than that of those that had resulted in a decrease. The implication is straight-forward: for addressing a technological barrier –in fact only ‘new high-tech product’ based on case evidence– niche strategies are expected to be more consistent in their influence to decrease the magnitude, as opposed to social barriers.

7.2.3. EXTERNAL FACTORS

With a single exception, external factors were only observed to diminish the magnitude of the factors. At first sight, the implication might seem as if these factors can be trusted upon to primarily (partly) remove the core and contextual factors. However, such a conclusion would be erroneous based on the following two arguments. Firstly, there are numerous situations when external factors can be conceived to increase the magnitude: government policies which may deter the progress of a technology in the benefit of another, demonstrations of competing technologies that convince customers to defer from adoption, etc. Secondly, the research methodology and the selection of cases could have eluded by design coming across such effects. For instance, two of the technologies were successful diffusion stories; and the latter –PEMFCV– was primarily researched using sources interested about the current or future diffusion of the technology. To sum up, although external factors were not observed to have unintended consequences –as was the case with niche strategies on ‘institutional aspects’ or ‘customers’ barriers– they can be conceived to be leveraged also towards increasing the magnitude of the barriers.

The implication above was at a market-level perspective. However, at a company-level –including network of companies– external factors can be fairly confidently leveraged to diminish the magnitude of the barriers, since their objectives would be generally aimed in that direction. For instance, one of the most impactful and prevalent external factors was ‘internal R&D’; including ‘collaborative R&D’. The knowledge of the technology and the product performance and/or costs were improved as a result of this action. Furthermore, this factor was regularly coupled with or had preceded niche strategies.

This connects to another interesting point to be made on the topic of external factors. They can be divided in purely external factors –such as an economic downturn, autonomous improvements in other industries– or factors external to the particular niche strategies, but connected nevertheless to the market actors –such as internal R&D, lobbying by OEMs, etc. This latter typology can be seen as alternative or additional way in which actors can guarantee or improve the success of current, or respectively future, niche strategies.

In certain cases or for certain external factors, the first typology can also be coupled with niche strategies. For instance, government policies in Japan aimed at the diffusion of fuel-cell vehicles were instrumental in the up-scaling of the infrastructure, R&D, regulatory environment and customer awareness. Motor companies, such as Toyota, which were involved in industry-government partnerships made great use of these developments. Equally so, by involving the government bodies in the demonstration projects there would have been a greater confidence in the level of safety guaranteed by the technology.

A very relevant observation regards the span of core and contextual factors which can be influenced by external factors: five of the six core ones, and four of the six contextual ones investigated. Among the three change drivers, they are the top influencer, if counting by this measure.

Furthermore, except for ‘accidents or events’, for all of the core and contextual factors which were (partly) removed by niche strategies, there is an available external factor to double that influence. In other words, niche strategies do not have any unique useful influence on the barriers or the contextual factors, which cannot be achieved by external factors as well. However, note that the conclusion eludes the size of the impact; i.e. niche strategies may prove to be more effective –resource and/or time-wise– than external factors, or they may prove to be key in completely removing certain barriers such as ‘customers’.

7.2.4.CHANGE OF MARKETS

The change from one market to another –for e.g. from racing to a consumer market, or from aviation to automotive– had an impact on how the barriers were interpreted. Therefore, the market context is dependent on such considerations.

It could also be argued that the choice of niche strategies explicitly entails the selection of the market niche. It would follow that the mere choice a niche strategy can also have an impact on how the barriers are interpreted, and therefore the change from one market to another could be included under former aspect, i.e. (2). However, note that in section 3.1.4 niche strategies were defined as a response to the market situation. Thus, by using the presumed rationale above the definition would not hold true anymore, since niche strategies would then impact the strategic analysis of the barriers to large-scale diffusion, even before they would be decided upon. The argument would thus be inconsistent with theory laid out in the initial chapters.

Note that only a handful of core and contextual factors were influenced by the ‘change of markets’: ‘institutional aspects’, ‘new high-tech product’, ‘accidents or events’, and ‘knowledge of technology’. However, the importance of this change driver is nevertheless significant, since it was the only one observed to purposely remove the contextual factor ‘accidents or events’. In the DCT case, the negative connotation of the technological superiority in racing was made irrelevant when moving to a consumer market. But moving to a consumer market can also have some downsides to the barriers, as proven in the ABS case.

Lastly, the impact of the ‘change of markets’ can be fairly predictable, at least based on the case evidence. This means that managers can leverage this factor effectively; unfortunately, they are nevertheless limited by its scope.

8. OPTING BETWEEN CATEGORIES OF STRATEGIES

This chapter concludes upon the answer to the 4th research question, i.e. "Based on which criteria should companies opt for a wait-and-see, niche or large-scale introduction strategy?" The synthesised information which forms the basis of the argumentation of this chapter can be found under Table XVII.

A wait-and-see strategy would be appropriate when there are many barriers hampering large-scale diffusion. In addition, the strategy rendered itself useful in the presence of internal product development and a changing market context. Companies can continue to work on the technology without introducing any product on the market, while in the same time taking advantage of the positive changes on the market context –i.e. barriers decreasing in magnitude on the basis of purely external factors or other actors– or they may also proactively influence the change in barriers via press demonstration, press releases, expos, or other such means.

Niche strategies were found to be used when there were remaining barriers to large-scale diffusion. Mass market introduction was used when there were no more barriers to large-scale diffusion. These two findings are in line with those referenced in section 2.5 "Strategic Options".

But companies can start preparing for a mass market strategy even before there are no more barriers to large-scale diffusion, provided that managers have the means to influence the remaining ones without the need for niche strategies. For instance, they could leverage external factors to influence the market context prior to the large-scale product introduction. Furthermore, given the two implications from chapter 7 that (a) niche strategies may sometimes increase the magnitude of the barriers and (b) their (diminishing) effect can be doubled by external factors, then this option would appear as a safer alternative. The key assumption undermining this conclusion is whether external factors are at least as effective as niche strategies in completely removing barriers.

In addition, it could be observed that niche strategies can be used for the gradual ramp-up of production, which becomes essential in lowering down the manufacturing costs of the product.

9. SEQUENCES OF NICHE STRATEGIES

9.1. LOGIC AND RATIONALE BEHIND SEQUENCES OF NICHE STRATEGIES

This sub-section concludes on the answer to the 5th research question, i.e. "What could be the logic and rationale behind sequences of niche strategies for market creation?" Based on Table XVIII, from section 6.4.1, the initial typology of logical sequences could be populated with case examples, as presented on the right-hand side of Figure 59.

Three generic types of sequences were observed: (1) exploitation- or (2) exploration-oriented emergent ones, and (3) exploitation-oriented deliberate ones. As presumed initially, exploration-oriented deliberate sequences are conceptually conceivable, but not necessarily observable.

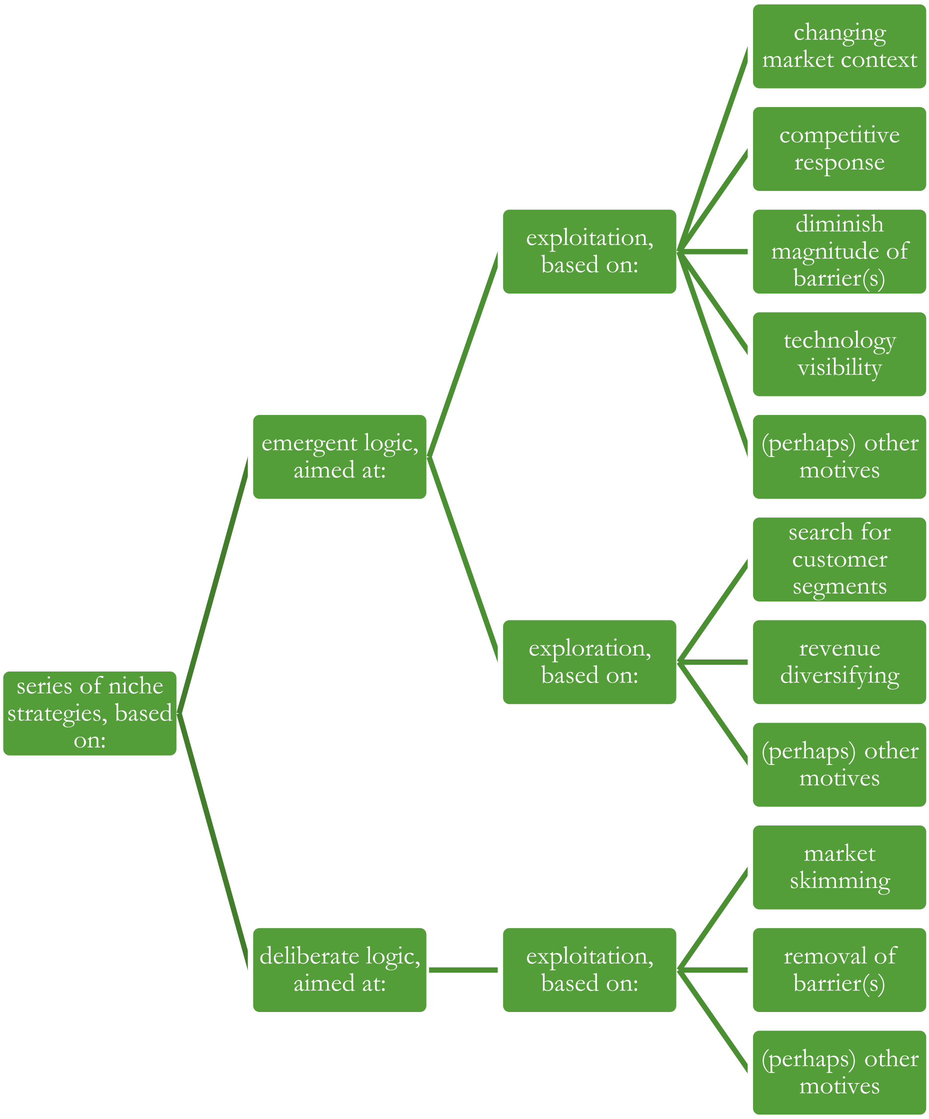


Figure 59: Logic and rationale behind sequences of niche strategies

The majority of the observed rationales fall within the exploitation-oriented typology. Given the exploratory nature of the study, and the relatively limited number of cases investigated, this observation alone could not substantiate a definitive conclusion on the matter. Nevertheless, we may note that an exploration-oriented sequence would be primarily possible only for technologies having a large scope of use or a great degree of modularity.

Exclusively within the automotive industry no two rationales were the same. This hints at the diversity and the large scope of sequences of niche strategies within the industry itself. When looking across industries, there were nevertheless two examples of rationales which were observed for two of the cases: market skimming and search for customer segments. Admittedly, also 'diminish the magnitude of barrier(s)' and 'removal of barrier(s)' are very similar to one another; there is a difference though in the degree to which external factors had been used in parallel to the sequence, and this carries more weight for the latter of the two.

The initial two-level categorization of sequences from sub-section 3.3.3 had proven comprehensive-enough. As noted earlier, there were no two completely identical rationales among the three cases. The up-front structure allowed for an easy classification of the diverse range of possibilities.

From a managerial perspective, the current typology appears to be quite generic to yield itself useful enough. Despite this downside, the suggestion for further research is not directed towards this purpose. Remember that the sequences and the rationales were significantly diverse, which would be indicative of the fact that they are very much case and market context dependant. Other avenues for future research –on the topic of sequences– would be more relevant, as presented under sub-section 9.3.

9.2. SEQUENCES OF NICHE STRATEGIES IN THE AUTOMOTIVE INDUSTRY

9.2.1.OUTCOMES

This sub-section corresponds to the 6th research question, i.e. "What are logical sequences of niche strategies in the selected industry?" Overall the rationale behind sequences and the types of niche strategies used varied across cases. The bottom line would be that segmenting down to the individual niche strategies, there were no cross-case specific sequences.

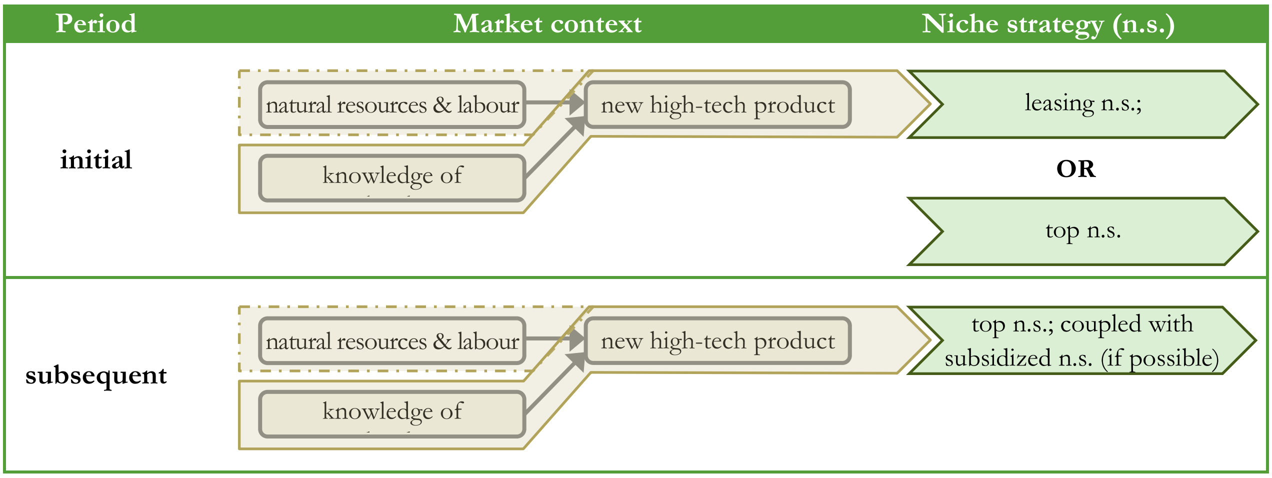
The conclusion comes as no surprise, since as early as chapter 3 it was stated that niche strategies represent a response to a market situation, which is embedded in overall market context. Furthermore, even in the limited sample of three cases, the status of the core and contextual factors varied significantly, and therefore any sequence of niche strategies would have had to account for this variation. To add to this complexity, two other generic aspects were discovered to have an influence on the barriers: external factors and the change from one market to another.

Nevertheless, per each typology of logic there were several sequences observed. The examples were dependant on the specific market context of the case and cannot be generalized across-cases. They were listed accordingly under section 6.4.2.

In conclusion, logical sequences that would apply across the automotive industry were not found. However, case specific examples were found per each particular typology of logic.

9.2.2.ILLUSTRATION

One example could potentially be elaborated upon as an illustration of the concept of sequences of niche strategies for market creation. The example can be classified under the exploitation-oriented deliberate sequences, and entails a market skimming rationale. It was also chosen since it the niche strategies used in the sequence represent a response to a factor which was found to be hampering large-scale scale diffusion across all three cases.



Note that the example 'top' followed by 'top' was used when expanding from another industry to automotive, rather than exclusively within automotive. Nevertheless, the case could be highly plausible also within automotive.

9.3. THEORETICAL IMPLICATIONS OF SEQUENCES OF NICHE STRATEGIES

The up-front theoretical implication to be derived from this exploratory research on the topic of sequences of niche strategies is that the further development of the theory shows potential. Each case illustrated at least one example where a sequence had been used: either on an emergent-basis or a deliberate one.

To develop such a theory, several aspects would be required, as follows: (1) performing an investigation of the impact of each individual niche strategy from the sequence on the factors, (2) detailing the concrete mechanisms by which niche strategies can impact the market context.

Firstly, on the topic of point (1) above, such an investigation would be very useful since with the initial market context known, the sequence could be constructed up-front. Furthermore, greater managerial benefits would be derived if it could be identified how the combined effect of niche strategies and external factors could be leveraged as part of a sequence.

Secondly, referring to point (2), it should be clearly delineated what constitutes the influence of the niche strategy versus that of an external factor. For instance, what this research had categorized as ‘internal R&D’ might be potentially attributed to the effect of ‘technological redesign’ by another research. Despite the fact that such decisions were clearly articulated for the three case studies in order to increase the reliability, the distinction should not render itself to the argumentation of the researcher. There should be a systematic way in which one may conclude whether a certain impact on the barriers was due to niche strategies or another factor.

The second theoretical implication is that sequences require a dynamic view on the market context, niche strategies, external factors and their impacts on one another. The revised conceptual model presented later under sub-section 10.1.1 attempts to meet this goal, as based on case evidence.

9.4. MANAGERIAL IMPLICATIONS OF SEQUENCES OF NICHE STRATEGIES

From a managerial perspective, sequences of niche strategies show potential in aiding managers mitigating a market context characterized by barriers to large-scale diffusion, and also using revenue-generating product introductions to subsequently influence this context. This can be done both by a deliberate up-front planning, but also in a more adaptive manner.

Secondly, sequences also command a word of caution, since some niche strategies can create barriers to large-scale diffusion in particular situations; at least on the 'customers' side and 'institutional aspects'. This would entail that managers should be wary of introducing their products without reflecting on their potential (negative) impact.

Thirdly, sequences should not be regarded in isolation of other means of influencing the barriers; for e.g. external factors or changing the market altogether. In fact, the individual niche strategies forming the sequence are best regarded as building blocks that may be arranged in a certain time-series, such that a certain higher goal is achieved. Towards meeting that same goal, other types of building blocks can be integrated in the grand scheme; for e.g. R&D, autonomous developments in other industries, lobbying, etc.

10. DISCUSSION

10.1. THEORETICAL CONTRIBUTIONS

10.1.1. CONCEPTUAL MODEL

When compared to the initial conceptual model presented under section 3.2, there are three main contributions added by the current research: (1) the creation of core and/or contextual factors by niche strategies, (2) splitting up external factors into two different types, and (3) adding a dynamic element to the model.

Firstly, the literature investigated prior to the case study research had eluded a certain type of impact of niche strategies: they may lead to the creation or increase the magnitude of core and/or contextual factors. The finding represents an important addition to the current body of literature. When considering that radically new high-tech products are introduced in several market niches –which may entail several instances of niche strategies– prior to large-scale diffusion (see Trevino Barbosa et al. 2011), it begs the question whether niche strategies themselves may be partly responsible for the occasional longer time-span of the market adaptation phase observed by Ortt & Delgoshaie (2008).

Secondly, the influence of external factors on core and contextual factors reported in the literature was supported by the case evidence. Additionally, it was uncovered that in the context of the niche strategies model, a further segmentation of external factors is required: (I) those commanded by the central actor, and (II) those purely external. The first type can be directly influenced by the central actor, and given the large scope of impact, it represents an important means for managers willing to diminish or remove the barriers to large-scale diffusion. The second type falls outside the decision power of the central actor, and typically represents spill-overs from other industries. There are nevertheless situations when even purely external factors can be influenced to some degree by the central actor –under specific arrangements, such as industry-government partnerships– but it does not have the ultimate decision authority over the factor.

Lastly, an important dynamic aspect has been added to the conceptual model. The market context determines the possible range of niche strategies. But at the same time, external factors can be used to directly impact the core and contextual factors; and so can niche strategies. Their effects are featured different under Figure 60 to highlight that the influence of niche strategies can only be observed once the product has been introduced in the market, and can therefore only impact the future market context. With the change of the core and/or contextual factors, some niche strategies may no longer be required since they may represent a response to a former market situation, i.e. which is no longer present.

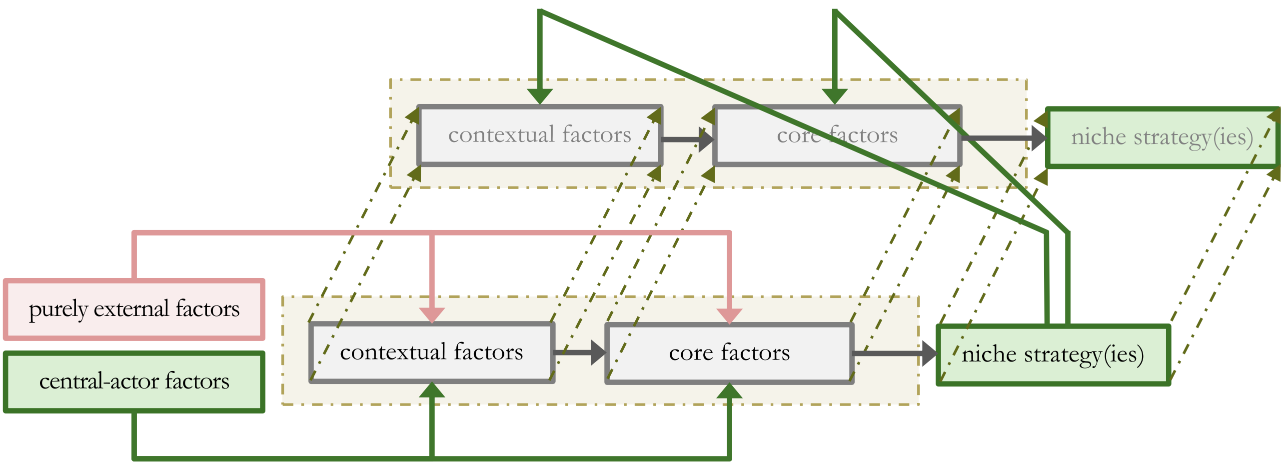


Figure 60: Conceptual model

10.1.2. OPERATIONAL MEASURES FOR SEQUENCES OF NICHE STRATEGIES

As part of the operational measures for the investigation of sequences of niche strategies, it was required to: (1) define niche strategy, (2) define sequences of niche strategies, and (3) devise a methodology for the investigation into sequences of niche strategies.

DEFINITION OF NICHE STRATEGY

In the context of the model by Ortt et al. (2013) and that of the current thesis work, a niche strategy represents a response to circumvent a market situation characterized by hampered large-scale diffusion, by which a company deliberately focuses on strategic niches in the effort to (1) develop a marketable product application or (2) market an already developed product in the existing regime, if and only if revenue can be derived from the market introduction.

DEFINITION OF SEQUENCES OF NICHE STRATEGIES

A sequence of niche strategies represents a series of niche strategies, in which the subsequent instances of the sequence are linked between one another on the basis of a specific rationale; the rationale can be based on either an emergent or deliberate logic. As a side note, the specific rationales observed from the case results are presented under Figure 59.

METHODOLOGY FOR THE INVESTIGATION OF SEQUENCES OF NICHE STRATEGIES

The conceptual model presented under section 10.1.1 is one of the tools for the investigation into sequences of niche strategies. Two visualisation tools were developed for the exploration of the cases: see Figure 11: Template for the visualization of the market context, and influence of niche strategies and external factors on the core and contextual factors and Figure 12: Template for the visualization of change in barriers.

10.1.3. REVISION TO THE MODEL ON THE PATTERN OF DEVELOPMENT AND DIFFUSION BY ORTT & SCHOORMANS (2004)

The case results commands some alterations to the pattern of development and diffusion, as posited by Ortt and Schoormans (2004), and presented under section 2.2. It was observed for the DCT technology that the market adaptation phase was discontinued by a second innovation phase. The conclusion was that the position of the different phases need not be regarded as fixed, and that they are better as building blocks of the technological life cycle.

However, this implication commands the reconsideration of how the phases are identified in the first place. If the first market introduction of the radically new high-tech product is no longer the only hallmark for the commencement of the market adaptation phase, and we can even talk of an apparent second 'first market introduction', then it becomes cumbersome to precisely define this phase; or the other phases for that matter.

An alternative way would be to define the bases also using the characteristics associated to them. This would prove unreliable, since technological niche continue well within the market adaptation phase. If for an extended period of time these technological niches would dominate, then based on the above recommendation that would hint the (re-)occurrence of the innovation phase. Conceptually this would be correct, but practically it would entail that different researchers can argue for different phases based on the same case evidence; instead of a definitive factual set of measures as in the initial model.

The resolution of this issue is not to be explored in this thesis. However, note should be given to this aspect by further research on the topic, particularly on how to redefine the phases to account for the re-occurrence of one or several of them.

10.1.4. ADJUSTMENTS AND ADDITIONS TO MODEL BY ORTT ET AL. (2013)

The seminal paper for the current research work was the article by Ortt et al. (2013) on the topic of niche strategies. The following paragraphs summarize the proposed list of improvements to the model.

REVISED LIST OF CONTEXTUAL FACTORS

As one of the research results, it emerged that the contextual factor 'natural resources and labour' was too narrowly defined in the initial model, since it did not include capital costs. Thus, either a new contextual factor was to be added or an existing –fairly similar one– would be expanded. The second option seems more appropriate for two reasons. Firstly, the contextual factor 'natural resources and labour' already points to the importance of resources. Secondly, the model implicitly punctuates that financial resources are important when commenting on the core factor 'suppliers': "[s]ometimes actors with considerable resources are required, for example to provide an infrastructure" (Ortt et al. 2013, p.4).

To sum up, the name of the contextual factor should be changed into 'natural resources, labour and capital'. Correspondingly, the recommended revised description of Ortt et al. (2013) would be: *Natural resources, labour and capital are required to produce and use a new high-tech product. Each of them can be required for the production system, for complementary products and services, or for the high-tech product itself. The lack of any of the three could block large-scale diffusion. Labour excludes the human capital that resides in the organization, and capital refers to substantial financial resources required in the aforementioned sense.* The reader is advised to note that according to the initial definition of 'labour' by Ortt et al. (2013), the term excludes the concept of human capital –i.e. the knowledge that resides in individuals of an organization.

Secondly, another contextual factor which was found missing from the initial list by Ortt et al. (2013) is 'installed base'. The concept refers to how the number of units of the good that have been sold can influence the availability of complementary products and services, in the presence of network externalities. As discussed under section 5.3.6, the proposal to incorporate 'installed base' in the list of contextual factors as a new factor, because: on one hand it elicits the reason for the emergence of the ('complementary products and services') barrier, and is therefore consistent with the definition of contextual factors; and, on the other hand, it significantly departs from the current list of factors by Ortt et al. (2013).

The revised list of the seven contextual factors is as follows: (1) knowledge of technology, (2) knowledge of application, (3) natural resources, labour and capital, (4) socio-cultural aspects, (5) macro-economic aspects, (6) accidents or events, and (7) installed base.

REVISED LIST OF NICHE STRATEGIES

In chapter 3, it was argued that the 'redesign' niche strategy should be split into 'technological redesign' and 'social redesign' niche strategies, given that the scope of the original term was too encompassing, as opposed to the other niche strategies. The revised descriptions of the strategies are as follows:

'technological redesign' niche strategy

"Knowledge of the technology is lacking and that affects the availability of the product or the production system and that in turn affects the availability of the product for a reasonable

'social redesign' niche strategy

Knowledge of the application of the product is missing or socio cultural aspects affect the availability of appropriate institutional aspects (laws, rules and standards) and thereby

price. Resources for the product or the production are lacking or very expensive and that affects the product's price." (Ortt et al. 2013, p.9)	*hamper diffusion. Socio-cultural aspects affect the availability of suppliers or customers." (Ortt et al. 2013, p.9)*

Following the PEMFCV case, we concluded that the ten niche strategies are incomplete. They do not account for the leasing of the technology in order to diminish the cost pressures on consumers. The new niche strategy is called 'leasing' niche strategy. The recommendation for the revised description is:

Leasing niche strategy	*A niche strategy can be adopted where the prohibitive ownership price of the new high-tech product are mitigated by leasing the technology to customers willing to use it. Ownership rights need not be transferred at the end of the lease.* *The prohibitive price can arise either on the basis of the lacking knowledge of the technology or due to the associated costs of natural resources, labour or capital.*	*Toyota Motor leased the first fuel cell cars, instead of charging for the entire ownership costs. This strategy can also be used to experiment with the technology in a relevant user context, before full-scale commercial introduction.*

Thus, the revised list of niche strategies is as shown under Table XIX. Please note that the description of those initially reported by Ortt et al. (2013) was presented under sub-section 2.4.3. For the new one –leasing niche strategy– please consult the description just above.

Table XIX: Final list of niche strategies as resulting from the current research work

1. Demo, experiment & develop n.s.	2. Top n.s.
3. Subsidized n.s	4. i. Technological redesign n.s.
4. ii. Social redesign n.s.	5. Stand-alone n.s.
6. Hybridization n.s.	7. Educate n.s.
8. Geographic n.s.	9. Lead user n.s.
10. Explore multiple markets n.s.	11. Leasing n.s.

NICHE-STRATEGIES AS HYBRID ENTITITIES

Niche strategies were observed to elicit or borrow certain characteristics of fellow counterparts. For example, a 'geographic' niche strategy can be used in combination with a price premium commanded from customers. In absence of the necessary market situation for the 'top' niche strategy, it would be more adequate to regard the former as a hybrid niche strategy targeting a certain geographic area, and on top of that also commanding a higher price from customers.

This has important theoretical implications, since the niche strategies need not be regarded anymore as individual, unchangeable blocks; rather they can present characteristics of several other strategies, provided that at least one is a response to the market situation. This latter restriction is imposed by the definition of the niche strategy.

Building further on the idea, the observation contributes towards diminishing one common concern with the positioning school, which argues that it reduces the strategy creation process to a selection from a restricted list of conditions (see Mintzberg et al. 1998, p.116). Since niche strategies should no longer be regarded as rigid blocks, managers can combine certain attributes from several, whilst still benefiting up-front from an encompassing selection to choose from in response to any of the encountered market situations.

10.2. MANAGERIAL APLICABILITY

The findings of the current research work include several contributions for managerial applicability. Firstly, as presented by the answer to the 2nd research question, managers can use the observed rule of thumb that technological barriers which were not observed at the start of the market adaptation phase will not appear spontaneously mid-way through the phase. The finding can help reduce the uncertainty with regard to unanticipated changes in the market context.

Secondly, by referring to the answer to the 3rd research question, managers can become aware of the three drivers that can influence –both positively and negatively– the magnitude of the core and contextual factors: (1) niche strategies, (2) external factors and (3) change of market context. More granular recommendations with regard to the use of niche strategies and/or external factors were given under sub-sections 7.2.2 and 7.2.3. For brevity they will not be repeated here.

The most important managerial take-away points from research question no. 4 relate to: (I) the use of the wait-and-see strategy, and (II) preparations for large-scale introduction in the presence of barriers to large-scale diffusion. For point (I), managers can continue to develop the product internally, and take advantage of the change in market context. For point (II), mass market strategy can be considered an option even prior to the complete absence of barriers, provided that external factors can be effectively used to remove the remaining core factors.

Specifically on the topic of sequences of niche strategies, companies can use the typology described under section 9.1 to explore potential rationales. Moreover, specific case examples can prove relevant for other technologies where a similar market context can be observed. The observed sequences can be used as templates for future product introductions, as was illustrated by Dunlop: the company essentially copied the initial sequence with some adjustments based on the prior experience. For the complete set of managerial implications of sequences, the reader is directed to refer to section 9.4.

10.3. LIMITATIONS

The first limitation is given by the analysis of multiple historical case studies. This might have induced a hindsight bias, given that the results were interpreted with an existing knowledge of the socio-technical outcome. Furthermore, by deriving the results from cases with a market adaptation phase of more than two decades, it might be possible to have eluded cases where a sequence of niche strategies was so effective that the length was reduced considerably.

The second limitation also derives from the design of the methodology. Note that the change in the barriers is observed from a market perspective. For individual manufacturers the market context may look different, if for instance they do not have access to a particular technology of the rights to use that technology. This might explain why throughout the case most statements were made with regard to the industry leader at any moment in time. For the other actors, the potential rationale in using sequences of niche strategies might not have been apparent given the dissonance in perspectives.

Thirdly, the selection criteria excluded technologies that are featured as 'optional' on cars. In this respect the research results are skewed towards critical or secondary components. Given that the managerial relevance of 'optional' features was not assessed, the research might have eluded an interesting area of study.

Lastly, the operational measures for deciding upon the pursued rationale from sequences of niche strategies were prone to errors in reliability. More comprehensive tools should be developed in which the decision on the rationale stems not from argumentation and typology, but rather from a set of objective criteria. In this respect, the research might have left unexplored potentially interesting sequences.

10.4. FUTURE RESEARCH

The suggestions for further research are broken-down under specific topics, as follows: those related to (1) change drivers for barriers, and (2) sequences of niche strategies.

10.4.1. CHANGE DRIVERS

Future research can focus on providing a greater level of depth with respect to the individual impact of each strategy on the market context. Although niche strategies were observed to increase the magnitude of the barriers, it is not yet clear what are the specific conditions under which this impact may be observed.

Furthermore, it would be reasonable to believe that not all niche strategies would have this effect. Isolating the ones that would and the ones that would not, should prove helpful towards assessing the (potential) detrimental impact of certain niche strategies on the market context.

Secondly, understanding the influence of external factors shows promising avenues for further research. These factors have proven essential means for managers in influencing the market context, and their scope exceeds that of niche strategies. The key aspect to be assessed regards the difference in impacts of external factors versus niche strategies. Conceptually both may have proven useful in diminishing the magnitude of the barriers, but there is no clear understanding of when only one of the change drivers would prove effective, whereas another would not.

The dynamic model presented under sub-section 10.1.1 can be further improved if the relationships between external factors –either purely external or those under the central-actor's decision authority– and niche strategies are also investigated. This research had hinted at the large benefits emerging when niche strategies are used in parallel factors such as 'government policies'. Their effects can be designed to be complementary, and ultimately accelerate the rate of diffusion.

The outcomes would be helpful in increasing the managerial relevance of both the niche strategies model and that of sequences.

10.4.1. SEQUENCES OF NICHE STRATEGIES

The current exploratory research revealed further potential in the development of the theory on sequences of niche strategies. In this respect, the first and foremost suggestion for further investigation is the analysis of a more expansive set of cases based on more reliable operational measures.

Towards that goal, a case survey of several historical case studies would be appropriate. This would require the development of coding scheme, for the systematic review of cases. Appendix 5 presents a proposal for the coding scheme, which may be readily used by other researchers.

Perhaps the greatest managerial relevance of sequences of niche strategies resides in the application of the model for forward-looking scenarios. Provided that the influence of niche strategies is known, a deliberate sequence can be devised on the basis of which a hypothesised market context would emerge. The actual developments could be compared against the ones posited by the use of the model.

Lastly, future research should focus on refining the results regarding the rationale behind sequences of niche strategies. Currently, under each of the four categories there are merely examples; whereas further investigation into the topic could come up with a more comprehensive categorization of these rationales.

11. APPENDIX

11.1. APPENDIX 1: DEFINITIONS BY ORTT ET AL. (2013)

11.1.1. CORE AND CONTEXTUAL FACTORS

The following table is a literal extract from Ortt et al. (2013, p.4), and describes the actors, factors and functions necessary for large-scale diffusion.

Table XX: Core and contextual factors as defined by Ortt et al. (2013)

Factors	Description
New high-tech product	The product can be defined and distinguished using three elements: the functionality provided by the product, the technological principle(s) used and the main components in the system (first tier of subsystems). The unavailability of (one or more components of) the product means that large-scale diffusion is not (yet) possible. The product needs to have a good price/quality compared to competitive products in the perception of customers before large-scale diffusion is possible.
Production system	Availability of a good production system is required for large-scale diffusion. In some cases a product can be created in small numbers as a kind of craftsmanship but industrial production technologies are not yet available. In that case large-scale diffusion is not possible.
Complementary products and services	Complementary products and services refer to products and services required for the production, distribution, adoption and use. The product together with complementary products and services forms a socio-technological system. The unavailability of elements in that system means that large-scale diffusion is not (yet) possible.
Suppliers (network of organizations)	The producers and suppliers refer to the actors involved in the supply of the product. Sometimes multiple types of actors are required to supply the entire system. In that case a kind of coordination (network) is required. Sometimes actors with considerable resources are required, for example to provide an infrastructure. If one or more vital roles, resources or types of coordination are not present in the socio-technological system, large-scale diffusion is blocked.
Customers	The availability of customers means that a market application for the product is identified, that customer segments for these applications exist and that the customers are knowledgeable about the product and its use and are willing and able to pay for adoption. If applications are unknown or if customer groups do not exist, are not able to obtain the product or are unaware of the benefits of the product, large-scale diffusion is blocked.
Institutional aspects (laws, rules and standards)	The regulatory and institutional environment refers to the laws and regulations that indicate how actors (on the supply and demand side of the market) deal with the socio-technological system. These laws and regulations can either stimulate the application of radically new high-tech products (such as subsidy that stimulates the use of sustainable energy) or completely block it (such as laws prohibiting something).
Knowledge of technology	The knowledge of the technology refers to the knowledge required to develop, produce, replicate and control the technological principles in a product. In many cases a lack of knowledge blocks large-scale diffusion.
Natural resources and labour	Natural resources and labour are required to produce and use a new high-tech product. These resources and labour can be required for the production system, for complementary products and services or for the product itself. In many cases a lack of resources and labour block large-scale diffusion.
Knowledge of application	Knowledge of the application can refer to knowing potential applications. If a technological principle is demonstrated but there is no clue about its practical application, large-scale diffusion is impossible. A lack of knowledge of the application can also refer to customers that do not know how to use a new product in a particular application. In that case large-scale diffusion is not possible.
Socio-cultural aspects	Socio-cultural aspects refer to the norms and values in a particular culture. These aspects might be less formalized than the laws and rules in the institutional aspects but their effect might completely block large-scale diffusion.

Factors	Description
Macro-Economic aspects	Macro-Economic aspects refer to the economic situation. A recession can stifle the diffusion of a new high-tech product.
Accidents or events	Accidents or events such as wars, accidents in production, accidents in the use of products can have a devastating effect on the diffusion of a new high-tech product.

11.1.2. NICHE STRATEGIES

The following table is a literal extract from Ortt et al. (2013, pp.6-9), and describes the ten different niche strategies developed by the aforementioned authors. The reader is advised to note that the references for the case examples were eluded.

Table XXI: Niche strategies as defined by Ortt et al. (2013)

Generic niche strategies	Description of the niche strategy	Case examples
1 Demo, experiment and develop niche strategy	A niche strategy can be adopted to demonstrate the product in public in a controlled way so the limited quality of performance is not a problem. As part of the strategy experimenting with the product is important to develop the product further, for example in a research environment.	Telegraphy was demonstrated in multiple cities before it was put into use […] Video telephony was demonstrated on multiple world exhibitions before marketable products emerged in the 1960s […]
2 Top niche strategy	A niche strategy can be adopted where hand-made products can be made to order, in small numbers, for a specific top-end niche of the market. A skimming strategy can be adopted in which the top niche of customers is supplied first with a special product.	The first cars were made-to-order and crafted by hand for a top-niche of the market […]. The strong fiber Dyneema was hand-made and used in a special niche before large-scale production was possible […].
3 Subsidized niche strategy	A niche strategy can be adopted where the product is subsidized if the use of the product by a particular segment of users is considered as societally relevant or important.	Video telephony for deaf people was funded by EU budgets […]. New clean energy technologies are subsidized […].
4 Redesign niche strategy	A niche strategy can be adopted where the product is introduced in a simpler version that can be produced with the existing knowledge, less use of resources and therefore for a lower price. A niche strategy can be to explore an application where institutional aspects are more favorable. Mostly leads to redesign. A niche strategy can be to explore an application where suppliers or customers have no resistance to produce and use it. Mostly leads to redesign.	Furniture design after WW2 was adapted because resources such as steel and wood were scarce and needed to rebuild countries. The first personal computers were apart from the first professional applications used as kind of typing machine rather than using their full potential […]. The contraceptive pill was introduced for skin irregularity because approval as a contraceptive was controversial […].
5 Dedicated system or stand-alone niche strategy	A niche strategy can be adopted where the product is used in stand-alone mode or a dedicated system of complementary products and services is designed (e.g., a local network when an infrastructure is not available on a wider scale).	Telephony was first used to contact the telegraph office, as a means for intra-company communication, and as a dedicated burglar alarm when the telephony infrastructure was not yet available […].

Generic niche strategies	Description of the niche strategy	Case examples
6 Hybridization or adaptor niche strategy	A niche strategy can be adopted by which the new product is used in combination with the old product and thereby all existing complementary products and services can be re-used. Or an adaptor/convertor is provided to make the product compatible with existing complementary products and services.	Hybrid car is a way to create fuel efficient cars when the infrastructure to use fully electric cars is not yet available […].
7 Educate niche strategy	A niche strategy can be adopted aimed at transferring the knowledge to suppliers. An educate and experiment (pilot) niche strategy can be adopted aimed at increasing customer knowledge.	Bell labs organized conferences to transfer knowledge regarding semiconductors and transistor technology to manufacturers such as Raytheon. Bell also stimulated universities to develop this knowledge […].
8 Geographic niche strategy	A niche strategy can be adopted where institutions (laws and rules) are relatively easy to arrange or are less strict. A niche strategy can be adopted in another geographic area where resources, suppliers or customers are available. A niche strategy can be adopted in another geographic area where suppliers are available and not hampered by these unexpected events or accidents.	After some terrible accidents Nobel was forced to move the production of Dynamite to the UK, that also stimulated the creation of a new market segment […].
9 Lead user niche strategy	A niche strategy can be adopted finding innovators or lead users. These lead users can co-develop the product and innovators are willing to experiment with the product.	Sport equipment developed by top sporters themselves […].
10 Explore multiple markets niche strategy	A niche strategy can be adopted in which multiple customer applications can be explored. Visibility of the first applications might stimulate explorative use in new applications.	At first it was unclear in what type of applications memory metal could be used […].

11.2. APPENDIX 2: TEMPLATE FOR DATA COLLECTION

1. Sources and Reliability of Data

1.1. Main sources

(insert list of main sources)

1.2. Reliability of data

Definition

O logical functionality, principle and components, general agreement on the unit, stable over time
O cross/checked, well documented but some uncertainty regarding one of the following aspects: choice of components or functionality or principle.
O alternative definitions of product/technology (schools)
O uncertain: quick changes of unit over time: unstable unit
O very uncertain: quick changes of unit over time and no clear schools of defining product/technology

Is the product technology definable in terms of functionality/principle and components in a way that it is stable over time?

- If yes: case can be assessed
- If no: true evolution

Hallmarks

O certain cross/checked, well documented
O cross/checked, well documented but some uncertainty large-scale diffusion
O multiple sources but uncertainty
O uncertain
O very uncertain

Conclusion: are hallmarks accessible with an accuracy that is relatively large compared to the time interval between hallmarks?

- If yes: pattern can be assessed
- If no: pattern become a constant flux and cannot be assessed

Actors

O certain cross/checked, well documented
O cross/checked, well documented but some uncertainty
O multiple sources but overview needs to be completed
O uncertain
O very uncertain

Strategies

O certain cross/checked, well documented
O cross/checked, well documented but some uncertainty
O multiple sources but strategies are not yet complete
O uncertain
O very uncertain

Subsequent applications

O certain cross/checked, well documented

O cross/checked, well documented but some uncertainty
O multiple sources but uncertainty
O uncertain
O very uncertain

2. Definition of the Product/Technology

2.1. Functionality of product

(describe)

2.2. Working principles of the technology

(describe)

2.3. Components of technological system in the product

(describe)

3. Pattern

3.1. Pattern data

Date	Remarks	Source
yyyy	(insert literal citations only)	(insert source)

3.2. Discussion pattern

(describe pattern and inconsistent sources)

3.3. Pattern overview

Hallmark	Year	Delta
Invention		
First application		
Commercialization (market intro)		
Large-scale industrial production		
Sales take-off (market stabilization)		

3.4. Picture of the pattern

(insert picture of the pattern; see Appendix 3: Patterns of development and diffusion)

3.5. Subsequent strategic niches

Market applications	Description	Year	Source
(coding)	(describe)	yyyy	(insert source)

3.5. Market actors and factors

Market actors and factors during […] phase	Description of their influence or role	Source
(coding)	(insert literal citations only)	(insert source)

3.6. Market strategies

Strategies	Description of their influence or role	Source
(coding)	(insert literal citations only)	(insert source)

11.3. APPENDIX 3: PATTERNS OF DEVELOPMENT AND DIFFUSION

11.3.1. DUAL-CLUTCH TRANSMISSION (DCT)

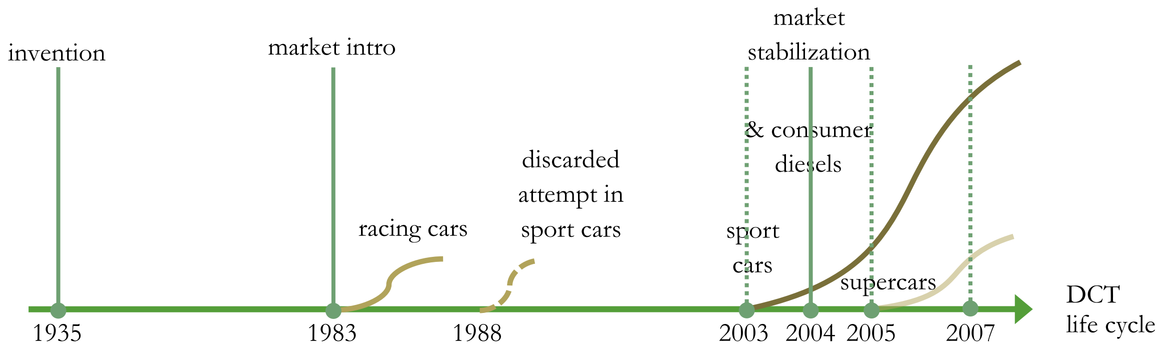


Figure 61: Pattern of development and diffusion – DCT technology

11.3.2. ANTI-LOCK BRAKES (ABS)

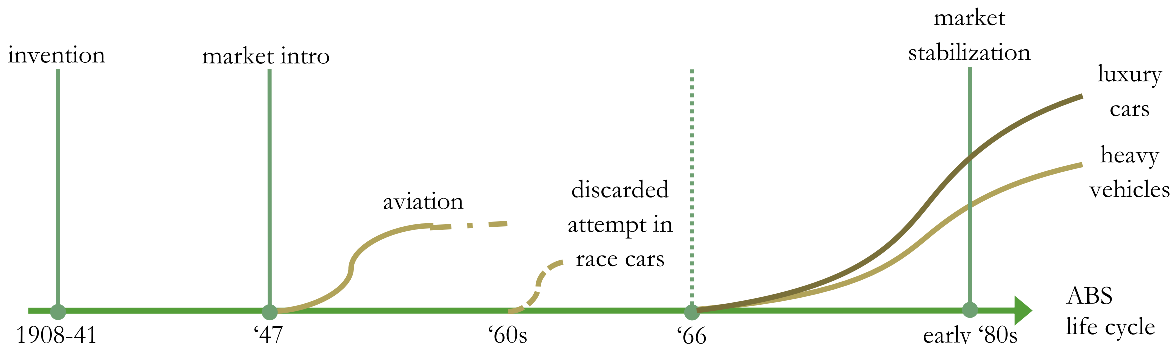


Figure 62: Pattern of development and diffusion – ABS technology

11.3.3. PROTON EXCHANGE MEMBRANE FUEL CELL VEHICLE (PEMFCV)

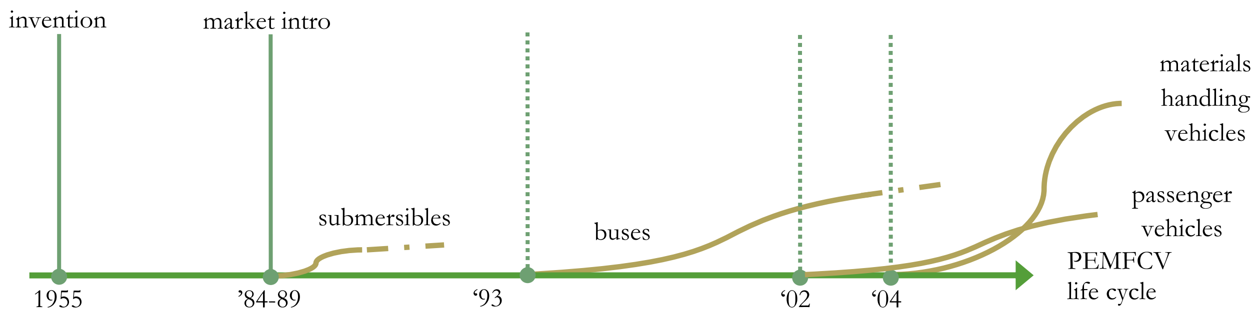


Figure 63: Pattern of development and diffusion – PEMFCV technology

11.4. APPENDIX 4: CASE REPOSITORY

For brevity, only the sections containing literal citations will be listed herewith. The reader is advised to note that the section concerning the definition of the product/technology is summarized in the case report; so is the pattern discussion. For the picture of the patterns please refer to Appendix 3: Patterns of development and diffusion.

11.4.1. DUAL-CLUTCH TRANSMISSION (DCT)

3. Pattern

3.1. Pattern data

Date	Remarks	Source
1935	"Kégresse […] after leaving the company in the mid-1930s focused his engineering abilities on another technology: transmissions. […] Manual transmissions of the time were cumbersome […]. Kégresse's system addressed this by automating the gearshift. In 1935, he patented [researcher's note: actually in 1935/36 in claim filed in France, and in 1939 published in US] his Autoserve transmission design, that used two clutches; the first engaged even gears, while the second engaged odd gears."	http://ae-plus.com/milestones/adolphe-kgresse-developed-the-dual-clutch-transmission
1935	"After leaving the Citroën company he developed in 1935 the AutoServe gearbox-transmission system"	http://self.gutenberg.org/article/whebn0004283823/adolphe%20k%C3%A9gresse
1935-36	1935/39: "Hydraulic change gear device for automobile vehicles US 2163202 A" 1936: "Hydraulic clutch mechanism US 2143321 A"	https://www.google.nl/patents/US2163202?dq=kegresse+1935&hl=en&sa=X&ei=9tc8VfLgBcHIPIuEgcAN&ved=0CEMQ6AEwBQ
1939	"The design principle of the twin- or dual-clutch transmission originates in a patent by Kegresse [1] back in 1939. The idea behind this transmission concept is to split a manual gearbox into two halves."	(Goetz et al., 2005, p. 951)
1939	"In the 1920s, Andre Citroën's collaborator, Adolph Kégresse, made important developments in this area, and in 1939 ZF filed [researcher's note: perhaps referring to "Power transmission mechanism US 2150950 A"] a patent for a dual-clutch gearbox. But it was not until the mid-1980s that a feasible solution for Porsche was established. This was named Porsche Doppler-Kupplungs (PDK, or double clutch device) used in 1985 by Porsche's 956 Gruppe C car and Audi's quattro S1 rally car."	http://www.lufteknic.com/trans.html#Tiptronic
1939	"Kégresse installed his system on a 1939 Citroën Traction Avant to test his technology. It worked, but even with its undoubted benefits the system was never taken any further because traditional torque converter automatic technology was more cost effective. For all of Kégresse's foresight, his system was not looked at again until the 1980s […]"	http://ae-plus.com/milestones/adolphe-kgresse-developed-the-dual-clutch-transmission
1939	"In 1935, he patented his Autoserve transmission design, that used two clutches; the first engaged even gears, while the second engaged odd gears. The design was based on a concentric clutch arrangement, where both clutches shared the same plane. Kégresse installed his system on a 1939 Citroën Traction Avant to test his technology"	http://amsdottorato.unibo.it/5683/1/Olivi_Davide_tesi.pdf
1939	"The man who invented the dual-clutch gearbox was a pioneer in automotive engineering. Adolphe Kégresse is best known for developing the half-track, a type of vehicle equipped with endless rubber treads allowing it to drive off-road over various forms of terrain. In 1939, Kégresse conceived the idea for a dual-clutch gearbox,	http://auto.howstuffworks.com/dual-clutch-transmission3.htm

	which he hoped to use on the legendary Citroën "Traction" vehicle. Unfortunately, adverse business circumstances prevented further development.”	
1940	“Dual clutch transmissions were already being developed in the 1940s. The original intention was to furnish heavy commercial vehicles with technology which provided for driving without power interruption. Serial production was not achieved, however.”	(Naunheimer et al., 2011, p. 172)
1970s	“The engineers at Zuffenhausen had been intermittently tinkering with the idea of a fast-shifting dual-clutch automated manual transmission since the 1970s in the form of the Porsche DoppelKupplung, or Porsche dual-clutch transmission.”	(Andropoulos, 2015)
1980	“The DCT was invented before World War II, but the idea sat on the shelf until the mid-1980s when Porsche and Audi began using the technology in race cars.”	http://gearpatrol.com/2013/08/19/a-guide-to-dual-clutch-transmissions/
1980	“In the 1980s, Porsche and Audi took up this transmission concept again and developed a dual clutch transmission for racing cars. These transmissions were not suited to serial production because the control quality of the systems was not yet sufficient.”	(Naunheimer et al., 2011, p. 172)
1980s	“The first actual DCT came along in the 1980s when computers to control the shifts were compact enough: the PDK […]”	(Senatore, 2009, p. 95)
1980s	“For example, at the end of the 1980s a Porsche twin clutch gearbox (PDK) was being used in motor racing [1]. However, it never reached production.”	http://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/symposia_1/downloads_11/luk_k7_chap17.pdf
1980s	“After renewed interest in the 1980s [2, 3], where the twin-clutch design had been applied to race cars, only the advent of faster and more capable electronics at the end of the 1990s led to full interest from all major car and transmission manufacturers. In 2003, the twin-clutch transmission [4] was finally put into production for the first time.”	(Goetz et al., 2005, pp. 951–952)
1983	“PDK stands for PorscheDoppelkupplungsgetriebe, or Porsche “dual-clutch transmission.” […] It first appeared in a testing capacity as a five-speed in the 956 race car in 1983 before later migrating to the 962 (pictured above), in which it won its first race at Monza in 1986.”	http://blog.caranddriver.com/shift-this-a-history-of-porsches-sportomatic-tiptronic-and-pdk-transmissions/
1983-84	“The real question is "what took everybody else so long?" The Porsche-Doppelkupplungsgetriebe name dates from 1983, when the first experimental version was developed and used in a 956 Series-produced endurance race car A 956 with the experimental gearbox won a German national championship race, and a couple of years a 962, the 956's descendant, equipped with the gearbox won an international championship race at Monza, in Italy.” [researcher’s note: given that the race at Monza was won in 1986, the German national championship race must have been won in 1984, i.e. 1986-2=1984]	(Russ, 2008)
1983	“Patent description: In a control system for a vehicle automatic gearbox of the kind in which a change of gear ratio includes the disengagement of one friction device and the engagement of another friction device, timing means provide an overlap between switching an output signal to engage the ongoing friction device and switching an output signal to disengage the offgoing friction device. The timing means is controlled by a pressure switch responsive to pressure in the actuator of the ongoing friction device and may be inhibited when the torque demand is low, i.e. on a trailing throttle.”	http://worldwide.espacenet.com/publicationDetails/biblio?FT=D&date=19830112&DB=EPODOC&locale=en_EP&CC=GB&NR=2101243A&KC=A&ND=6
1985	“Both Audi and Porsche picked up on the dual-clutch concept, although its use was limited at first to racecars. […] Audi also made history in 1985 when a Sport quattro S1 rally car equipped with dual-clutch transmission won the Pikes Peak hill climb, a	http://auto.howstuffworks.com/dual-clutch-transmission3.htm

	race up the 4,300-meter-high mountain."	
1985	"Following the tiptronic and multitronic, Audi is now introducing the Direct Shift Gearbox - also with an automatic function - as a further landmark in its transmission technology. This transmission principle is not new to Audi: the technology of the twin-clutch transmission has its roots in motor racing. Audi used it in the legendary Audi Sport quattro back in 1985, with Walter Röhrl behind the wheel. It also proved its worth in the Audi Sport quattro S1, a rally car that was victorious in many events, including the legendary Pikes Peak hillclimb."	http://www.audiworld.com/news/03/082703/content.shtml
1985	"'DRIVING THE E2 was like travelling on a bullet. […] The PDK made the acceleration even crazier... Sometimes the E2 scared me when I dropped the clutch at 4500rpm. It was like an explosion'. The words are those of double World Rally Champion Waiter Röhrl in his revealing new book, Waiter Röhrl Diary: Memories of a World Champion. When this rally icon admits to being daunted by the 530bhp, Group B Audi Sport quattro S1 Evolution 2 after Audi Sport fitted an experimental, doubleclutch, semi-automatic, five-speed PDK gearbox in autumn 1985, you know this was some mean machine."	http://www.urquattro.fr/Web/Pages/Journaux/diversetrangers/JE08.html
1985	"The Audi Sport Quattro S1 used a "5 or 6 speed PDK (Porsche-Doppelkupplung) power shifted or manual gearbox" (source: http://www.tech-racingcars.eu/audi-sport-quattro-s1)"	http://www.tech-racingcars.eu/audi-sport-quattro-s1
1985-86	"The idea of a dual clutch setup is not new. In fact, both Porsche and Audi have used transmissions based on similar principles in racecars during the 1980s. Porsche's vaunted and incredibly successful 956 and 962C race cars benefited from the Porsche Dual Klutch, or PDK, transmission. In 1985, Audi itself used a dual clutch transmission in the Pike's Peak Hillclimb winning Sport quattro S1 rally car."	http://www.audiworld.com/features/tests/2004tt32.shtml
~1987	"[…] in March [1987], Audi Sport withdrew from Group B World rallying. […]. The end, too, for Audi Sport's PDK development. Both PDK Sport quattro S1 Evolution 2s survive, identifiable by more prominent radiator grilles enforced by the longer 'boxes. Rohrl acquired RE 15, the unused Acropolis car, with PDK and later sold it to an Austrian garage owner friend. Audi Sport sold RE 02, reconverted to six-speed manual, to Franz Wittman, first ever rally winner in a quattro, for rallycross. […] Rohrl revealed to me that RE 02's PDK gearbox, acquired as a spare, sits in his Bavarian garage; maybe one day historic car and pioneering 'box will be reunited."	http://www.urquattro.fr/Web/Pages/Journaux/diversetrangers/JE08.html
1988	"In 1988, the 965's specification was well advanced with most of the attributes described earlier. The name "969" first advanced in February, was confirmed in May. Significantly, that decision was made by the engineer s- with the marketers playing a passive role in these years at Porsche. In the same month, the planned volume for 1990 was upped to 2,500 cars at a price expected to be DM 180,000 ($100.000). […] December of 1988 was the decisive month for the 965 Ulrich Bez was unimpressed. "It was there as a concept" he said. "It was very complicated, far too expensive. It would have been a car to sell for 200,000 Deutchmarks or more and was not a replacement for the Turbo." Nor with its numerous uncertanties was the time scale for its further development in any way reliable."	(Ludvigsen, 2005)
1988 [presumably]	"The 969 had a simplified but still sophisticated four-wheel-drive system and Porsche's PDK automatic transmission with "Tip" control – unless buyers wanted a manual.[…] Launched as a 1991 model to replace the ongoing Turbo, the 969 model was priced at DM210,000 ($116,700) at the top of Porsche's range and was tooled for production of 2,500 cars per year. […] [T]he project that would result in the 969 was cancelled when it was within just 18 months of its launch. Sixteen prototypes were built and under testing worldwide in Porsche's typically thorough manner Tooling to manufacture the 969 was being made."	(Ludvigsen, 2005)

1988 [presumably]	"Porsche's dual-clutch PDK transmission (5), as developed in the 962 program, was slated to appear in the 969 – incredible because the 991 Turbo will probably be the first application some 15 years later."	(Ludvigsen, 2005, p. 114)
1991	"There were several attempts, from a test fitment to a 924S to a production-intent integration of PDK into the 944 Turbo. A 968 equipped with PDK was nearly readied for sale before ZF's Tiptronic was called in to pinch hit, and a stillborn successor to the 959 (dubbed 969) with PDK was killed a year before going on sale for 1991."	http://blog.caranddriver.com/shift-this-a-history-of-porsches-sportomatic-tiptronic-and-pdk-transmissions/
2000	"Our wet clutch expertise combined with our advanced control strategies is propelling us to market first with technology for a new concept automated transmission. This same technology, when applied to traditional automatics or continuously variable transmissions, provides improved fuel economy. […]"	(BorgWarner, 2000, p. 18)
2001	"Fuel-efficient DualTronic™ transmission technology is selected for 2003 production by a major European automaker."	(BorgWarner, 2014)
2002	"In 2002, Volkswagen presented [researcher's note: not the same as "introduced"] the first dualclutch gearbox intended for series production, the 6-speed DSG. The dual-clutch principle ensures higher efficiency and lower fuel consumption than a conventional automatic transmission."	http://en.volkswagen.com/content/medialib/vwd4/vw_international/4_company/4_3_overview_sustainability/Nachhaltigkeit/Data_Sheets/umweltpraedikatepar0034file-pdf/_jcr_content/renditions/rendition.file/umweltpraedikate_par_0034_file.pdf
2003	"The first DCT for passenger cars went into production in 2003. The goal of this model was to combine the advantages of manual transmissions with those of automatic transmissions."	(Naunheimer et al., 2011, p. 172)
2003	"Dualtronic™ transmission technology debuts on the Audi TT and VW Golf R32. "	(BorgWarner, 2014)
2003	"Meanwhile this summer [of 2003], […], Audi became the first VM to introduce the double-clutch technology on a volume production car. In August [2003], in a break with tradition, the carmaker first launched a right-handed version of the Audi TT 3.2 quattro coupe with 6-speed gearbox into the UK […] […] By mid-September, in Europe the dual-clutch gearbox will be fitted to the Golf R32."	(Stefanini, 2003, p.71)
2003	"The sporty flair of the Golf, the Audi A3 and the Audi TT is enhanced by the combination of the new dual-clutch DSG® direct shift gearbox with the powerful 3.2 l VR6 engine. The very fast gear-shifting of the DSG results in outstanding performance with a marked reduction in consumption even relative to conventional manual gearboxes. In future the DSG will also be fitted in diesel-engined vehicles, enhancing their performance and delivering even lower fuel consumption."	(Volkswagen AG, 2004, p. 50)
2003	"Volkswagen produced the first DCT-equipped production car, the 2003 Golf R32, a performance variant of its standard fourth-generation Golf. The car developed a cult following, in part because of its crisp handling and power, but also because its quick-shifting six-speed Direct-Shift Gearbox helped it achieve a 0-60 time of 4.4 seconds."	http://gearpatrol.com/2013/08/19/a-guide-to-dual-clutch-transmissions/
2003	"Continental Automotive Systems developed a control unit for a dual-clutch transmission, which entered production in 2003. In bracing itself for a booming DCT market, the company has further developed its control involving mechanical components based on the automaker [e.g. VW] requirements."	(Senatore, 2009, p. 96)
2003	"[T]he first series production DSG gearbox came out in 2003. It went into the Golf R32. Audi had already launched the TT coupe based on the same platform and it decided a 3.2-liter V6 and a clever gearbox would be great for boosting sales. At that time, Audi used the DSG moniker, but subsequently changed it to S tronic. The gearbox was developed by BorgWarner and built by the VW Group's Kassel factory	(Radu, 2014)

	located in the heart of Germany. The DQ250 can take up to around 350 Nm of torque, is mainly paired to 2-liter turbo engines and weighs 90 kg (200 lb) in front-wheel drive applications, so slightly more than a manual."	
2004	"Last year, we continued to extend the range of applications for Volkswagen's Direct Shift Gearbox (DSG®). As a result, the DSG is now available on the Touran, Golf, Golf GTI, Skoda Octavia, SEAT Altea and SEAT Toledo, as well as on the Audi A3 and Audi TT with high-torque diesel or petrol engines."	(Volkswagen AG, 2005, p. 23)
2004	"In 2004, we extended the Golf range to include the new version of the GTI. Its new 2.0 liter FSI®* turbo direct-injection engine with 147 kW/200 bhp boasts 280 Nm of torque from 1,800 rpm. Direct injection and turbocharging team up with other elements in the engine to provide highly efficient power delivery. With the six-speed gearbox, the GTI accelerates from 0 to 100 km/h in just 7.2 seconds – with the Direct Shift Gearbox (DSG®), acceleration time is 6.9 seconds."	(Volkswagen AG, 2005, p. 22)
2004	"The DSG was first introduced to the US in 2003 with the model year 2004 New Beetle TDI and Audi TT. The gasoline NB still used a slushbox for that year. 5th generation VW Jetta TDI starting in 2005.5 also got DSG."	http://www.myturbodiesel.com/wiki/vw-dsg-direct-shift-gear-transmission-and-audi-stronic-faq/
2004	"In 2002, Volkswagen produced the Golf R32 in Europe as a 2003 model year. It was the World's first production car with a dual-clutch gearbox (DSG) — available for the German market.[7] Due to unexpected popularity, Volkswagen decided to sell the car in the United States and Australia as the 2004 model year Volkswagen R32. […] Although the R32 looked similar to the 20th Anniversary GTI, it shared most major components with the 3.2 litre Audi TT, including the engine, four-wheel drive system, and both front and rear suspension geometries. For the US, five thousand cars were produced and intended to be sold over a two-year period. The allotment sold out in 13 months."	http://self.gutenberg.org/article/WHEBN0008348989/Volkswagen%20Golf%20Mk4#R32_.282003.29
2004	"Serial production of a dual clutch or DSG transmission has been untenable to date […]. Audi again proves its technical expertise and prowess by bringing this first-ever commercial application to the streets."	http://www.audiworld.com/features/tests/2004tt32.shtml
2004	"In Europe, fuel-efficient DualTronic [by BorgWarner] transmission technology was made available on five additional Volkswagen/Audi vehicles. […] Transmission products will benefit from increased penetration of automatic transmissions in Europe and Asia, and the continued ramp-up of DualTronic™ transmission modules in Europe."	http://www.borgwarner.com/en/Investors/AnnualReports/Documents/2004-annual-report.pdf
2004	"The spectacular Chrysler ME Four-Twelve supercar astonished the world when it was unveiled at the North American International Auto Show in Detroit in January. Now, complete with 850 hp quad-turbo V12 and Ricardo's innovative seven speed, dual-clutch transmission, […]"	(Lewin, 2004, p. 9)
2005	"Total BorgWarner DualTronic technology programs announced to date represent an expected 1.5 million transmissions per year at full production volumes, or possibly 10% of the European vehicle market."	http://www.borgwarner.com/en/Investors/AnnualReports/Documents/2005-annual-report.pdf
2005	"December 6, 2005 The 7-speed Dual Clutch Transmission (DCT) system developed for the 406km/h, 987bhp Bugatti Veyron sportscar will be shown for the first time by Ricardo at the 4th International CTI-Symposium held in Berlin this week."	http://www.gizmag.com/go/4909/
2005-06	"'This is a very high quality, and clearly very high cost operation," says Adrian Turner, manager of Ricardo's low volume production operation, of the manufacturing process. "It's more akin to an advanced prototype build than series production – we call it dedicated cell manufacture.' The cell system sees two technicians each assemble a single transmission a week."	(Lewin, 2006, p. 13)
2005-06	"Conditions in the Bugatti assembly area are akin to those of a scientific clean room,	(Lewin, 2006, p. 13)

	[…] Component tolerances are close to aerospace levels at 6-8 microns, and exotic materials include rare-earth magnets located on the gear selector forks for extremely precise position sensors mounted on the external casing to monitor the exact location of selectors. This information is used in the control strategy and helps rule out double gear engagements"	
2005	"A variation on the sequential manual gearbox, this technology--currently available only on Audi and Volkswagen production cars—[…] The Direct-Shift Gearbox (DSG) is standard in the forthcoming V6 version of the A3 Quattro--a testament to the new technology's excellent performance. […] The DSG transmission is also available in Audi's sports car, the TT, and the Volkswagen Beetle turbo diesel."	http://www.popsci.com/cars/article/2005-07/popular-science-automotive-buyers-guide
2005	"BorgWarner receives its first Automotive News PACE Award for its DualTronic® transmission system. PACE Awards honor superior innovation, technological advancement and business performance among automotive suppliers."	(BorgWarner, 2014)
2005	"DualTronic(TM) technology is currently available on a range of VW and Audi vehicles, including the VW Golf R32; the Audi TT; the diesel and turbocharged direct-injected gasoline engine versions of the VW Golf; the VW Touran; the VW Passat; the VW Jetta; the Audi A3 Sportback; the Skoda Octavia; and the Seat Altea, Toledo and Leon."	http://www.prnewswire.com/news-releases/borgwarner-to-supply-dualtronictm-wet-clutch-technology-for-getrag-transmissions-displayed-at-frankfurt-motor-show-54940572.html
2005	"The 7 DCT 50 dual clutch transmission introduced [note: only exhibited at Frankfurt autoshow; production began in 2008] in 2005 by ZF is a 7-speed dual clutch gearbox for standard drive."	(Naunheimer et al., 2011, p. 501)
2005	"Looking back on decades of experience with powershift tranmissions, ZF also presents [at IAA Frankfurt] the newly developed 7 DCT 50, a 7-speed dual clutch transmission system for sporty driving."	http://www.zf.com/100years/en_de/index.html#!/article/history:29451:100JahreZF:en_DE
2005	"New Jetta also available with double clutch gearbox Every fourth Golf GTI, every fifth Passat Variant fitted with DSG® [….] DSG®, first used by Volkswagen in the original Golf R32, does not use a torque converter and provides better levels of acceleration and fuel consumption in comparison to a manual gearbox – with improved driving comfort. […] This is a system which counters the arguments of automatic sceptics and increases sales: every fourth Golf GTI customer chooses the direct shift gearbox, which adds an even more impressive acoustic element to the acceleration off the starting line. Even customers of more comfort-oriented vehicles such as the Touran and Passat estate are interested, with every fifth Volkswagen customer choosing the direct shift gearbox. A new addition to the programme is the option to have the DSG® fitted in the Jetta, the compact and sporty mid-range saloon launched in August. Two TDI engines as well as the 147 kW / 200 bhp Turbo-FSI engine are available together with the direct shift gearbox for prices starting at 23,225 Euro."	https://www.volkswagen-media-services.com/en/detailpage/-/detail/New-interest-in-automatic-gearboxes-thanks-to-DSG/view/90128/5ea8784c3b654f0aef71f2c5bf76826f?p_p_auth=oGysM013
2005	"The engineers have brought the combination "TDI plus DSG" up to top performance for the Golf, Golf Plus, Touran and the new Passat, therefore creating a promising new area for the dual-clutch gearbox to be used, available from an additional charge of 1375 euros."	https://www.volkswagen-media-services.com/en/detailpage/-/detail/Double-benefit-TDI-engine-plus-DSG-gearbox/view/90028/6e1e015af7bda8f2a4b42b43d2dcc9b5?p_p_auth=oGysM013
2005	"More than 150 000 DSG gearboxes produced at the Kassel factory	https://www.volkswagen-

	[...] Since the launch of the DSG at the start of 2004, more than 150 000 customers have chosen this innovative gearbox.”	media-services.com/en/detailpage/-/detail/Double-benefit-TDI-engine-plus-DSG-gearbox/view/90028/6e1e015af7bda8f2a4b42b43d2dcc9b5?p_p_auth=oGysM013
2006	“In August, the Kassel plant announced the production of the 500,000th direct shift gearbox (DSG).”	(Volkswagen AG, 2007, p. 93)
2006	“The direct shift gearbox (DSG) has successfully established itself in the market. In 2006, we delivered almost twice as many vehicles with this innovative technology as in the previous year. As a result, we will be able to make this technology available for other vehicle classes and enhance it systematically.”	(Volkswagen AG, 2007, p. 112)
2006	“In addition to the Skoda Laura, DualTronic(TM) technology is currently available on a range of other VW and Audi vehicles, including the VW Golf R32; the Audi TT; the diesel and turbocharged direct-injected gasoline engine versions of the VW Golf; the VW Touran; the VW Passat; the VW Jetta; the Audi A3 Sportback; the Skoda Octavia; and the Seat Altea, Toledo and Leon.”	http://www.prnewswire.com/news-releases/borgwarner-dualtronictm-wet-clutch-technology-makes-its-india-debut-53613057.html
2007	“Commercialization of the dual-clutch transmission, however, has not been feasible until recently. Volkswagen has been a pioneer in dual-clutch transmissions, licensing BorgWarner's DualTronic technology. European automobiles equipped with DCTs include the Volkswagen Beetle, Golf, Touran, and Jetta as well as the Audi TT and A3; the Skoda Octavia; and the Seat Altea, Toledo and Leon.”	http://auto.howstuffworks.com/dual-clutch-transmission3.htm
2007	“The one millionth DualTronic® module is produced in Germany”	http://www.borgwarner.com/en/Company/History/default.aspx
2007	“Two Getrag transmissions on display at the 2005 Frankfurt Motor Show this week use BorgWarner's fuel-efficient DualTronic(TM) wet dual-clutch module technology. The programs will start production in 2007 and are for vehicle types that range from compact and mid-sized to luxury passenger cars and sport-utility vehicles. "We're pleased to announce Getrag as a new customer for DualTronic(TM) transmission technology," said Tim Manganello, BorgWarner Chairman and CEO.”	http://www.prnewswire.com/news-releases/borgwarner-to-supply-dualtronictm-wet-clutch-technology-for-getrag-transmissions-displayed-at-frankfurt-motor-show-54940572.html
2007	“Ford is the second major manufacturer to commit to dual-clutch transmissions, made by Ford of Europe and its 50/50 joint venture transmission manufacturer, GETRAG-Ford. It demonstrated the Powershift System, a six-speed dual-clutch transmission, at the 2005 Frankfurt International Motor Show. However, production vehicles using a first generation Powershift are approximately two years away.”	http://auto.howstuffworks.com/dual-clutch-transmission3.htm
2007	“Ford and transmission partner Getrag of Germany will make 200,000 dual-clutch transmissions a year at a Getrag-Ford factory in Kechnec, Slovakia, predicts Chris Guile, an analyst at CSM Worldwide in London. A Getrag official said the company would show both a Getrag-Ford dual-clutch system and a separate Getrag dual-clutch unit at the Frankfurt IAA next week [i.e. in 2005]. […] Construction on the partners' joint-venture plant began in July [2005]. Production of dual-clutch transmissions for cars will begin in mid-2007, Getrag spokesman Axel Guggenberger said.”	http://europe.autonews.com/article/20050905/ANE/509050838/ford-joins-the-shift-to-dual-clutch-gearboxes
2007-08	“The Company’s activities in fiscal 2007/08 focused on the series production start of the new 911 Carrera with more economical engine variants and the Porsche Doppelkupplungsgetriebe (PDK).” [p.89] “For the first time, Porsche has equipped a series production sports car with Porsche Doppelkupplungsgetriebe (PDK) instead of the Tiptronic S automatic	Porsche Group Annual Report 2007/08 https://bib.kuleuven.be/files/ebib/jaarverslagen/PORSCHE_200708.pdf

	transmission." [p.95]	
2007-08	"Last year's key innovations relating to the Group's powertrain offensive included the further development of the TSI engine family […] the first seven-speed direct shift gearbox (DSG), and the 2.0 l CommonRail TDI engine. […] In contrast to the previous direct shift gearbox, the clutches of the new seven-speed DSG launched in early 2008 are dry rather than oil-bathed, which improves efficiency."	(Volkswagen AG, 2008, p. 147)
2008	"February 5: 1 million DSGs Employees and management of the Kassel plant celebrate the production of its one millionth direct shift gearbox (DSG)."	(Volkswagen AG, 2009, p. 292)
2008	"Since the DSG dual-clutch gearbox was first launched, more than a million units have been sold, resulting in a new boom in automatic transmissions at Volkswagen. The proportion of new vehicles equipped with automatic transmissions has risen dramatically, from 5 to 10 percent with conventional transmissions to as much as 30 percent with the DSG. With the new 7-speed DSG, even more customers will automatically shift up to environmental protection."	http://en.volkswagen.com/content/medialib/vwd4/vw_international/4_company/4_3_overview_sustainability/Nachhaltigkeit/Data_Sheets/umweltpraedikatepar0034file-pdf/_jcr_content/renditions/rendition.file/umweltpraedikate_par_0034_file.pdf
2008	"There were bright spots. From its World Rally Championship racing experience, Mitsubishi developed the Twin-Clutch Sportronic Shift Transmission (TC-SST), a wickedly precise, highly responsive and adjustable dual-clutch transmission offered in its all-new Lancer Evolution when the 10th generation rally car arrived worldwide in 2008."	http://gearpatrol.com/2013/08/19/a-guide-to-dual-clutch-transmissions/
2008	"The 7-speed dual clutch transmission, a joint development of Porsche and ZF, enters volume production. The technology was developed in Kressbronn, Bradenburg, and Schweinfurt; the transmission is produced at the Brandenburg site."	http://www.zf.com/100years/en_de/index.html#!/article/history:30657:100JahreZF:en_DE
2008	"BMW rolled out the first dual-clutch assemble in January 2008 on the M3 model - it is known as M DCT that stands for M Dual Clutch Transmission."	http://www.autoevolution.com/news/how-dual-clutch-transmissions-work-5458.html
2008	"More widely known as the 7-speed DSG gearbox, the DQ200 is different to the original BorgWarner unit. Instead of a submerged multi-plate clutch pack, this uses two single-plate dry clutches. From the start, it was designed for lower torque applications and because it's also fitted to smaller cars, it needed to be lighter as well. The DQ200 usually takes up to 250 Nm of torque from VW's 1.6-liter diesel or around 170 Nm from the 1.2 TSI. It weighs 70 kilograms (150 lbs) and as far as we know, it's never been used on anything other than front-wheel drive cars. Since its launch in 2008, the unit has found its way into two generations of VW Golf and one of the Polo, plus sister cars from SEAT (Ibiza and Leon), Skoda (Fabia II and III, Octavia II and III) and Audi (A1 and A3)."	(Radu, 2014)
2009	"In the last decade, the necessary technical advances in electronics and hydraulics have come to fruition, and Porsche finally released the production version of the PDK for the 2009 model year 911 and Boxster/Cayman models."	(Andropoulos, 2015)
2009	"Hyundai is quite new in this sector, as the South Korean automaker displayed at the 2009 Geneva Motor Show the ix-onic concept car equipped with a 6-speed double-clutch transmission."	http://www.autoevolution.com/news/how-dual-clutch-transmissions-work-5458.html
2010	"The two millionth DualTronic® module set is built in France and Germany."	http://www.borgwarner.com/en/Company/History/default.aspx

2010	"Fiat's C635 dual clutch transmission was unveiled in 2010, with front wheel drive, all wheel drive, and manual versions."	http://www.allpar.com/mopar/transmissions/fiat-dct.html
2010	"Fuso [part of Daimler Group] is the first manufacturer worldwide to present a double-clutch transmission in commercial vehicles [i.e. light trucks; not clear whether it includes heavy trucks as well] Known as the "Duonic", this double-clutch transmission combines automated driving with the advantages of a manual transmission"	http://media.daimler.com/dcmedia/0-921-854990-1-1316186-1-0-0-0-0-1-11701-614240-0-1-0-0-0-0-0.html?TS=1280750166010
2011 (publication year)	"For compact and mid-range cars, the dual clutch transmission (DCT) with 6, 7 and 8 speeds is considered to have good market chances, especially for sport cars."	(Naunheimer et al., 2011, p. 69)
2014	Transcript: In 2014, Volvo Trucks introduces the new I-Shift Dual Clutch Gearbox. Dual clutch technology already exists on passenger cars, but Volvo Trucks is the first manufacturer in the world that has been able to adapt the system for heavy trucks.	https://www.youtube.com/watch?v=MR5iFgJBpYk
2014	"BorgWarner builds its 4 millionth DualTronic® clutch and mechatronic module sets in Tulle, France, and Arnstadt, Germany. "	http://www.borgwarner.com/en/Company/History/default.aspx

3.5. Market actors and factors

Market actors and factors innovation phase	Description of their influence or role	Source
price (competitiveness)	"Kégresse installed his system on a 1939 Citroën Traction Avant to test his technology [… T]he system was never taken any further because traditional torque converter automatic technology was more cost effective, and the upcoming WWII stopped the development of transmission technology."	http://amsdottorato.unibo.it/5683/1/Olivi_Davide_tesi.pdf
size of computers	"The first actual DCT came along in the 1980s when computers to control the shifts were compact enough: the PDK […]"	(Senatore, 2009, p. 95)
quality control of the systems	"In the 1980s, Porsche and Audi took up this transmission concept again and developed a dual clutch transmission for racing cars. These transmissions were not suited to serial production because the control quality of the systems was not yet sufficient."	(Naunheimer et al., 2011, p. 172)
Market actors and factors market adaptation phase	**Description of their influence or role**	**Source**
knowledge of the technology	"Besides requiring a learning curve, PDK was only reliable in the sense that it would reliably explode every so often, chucking shafts, gears, actuators, and the like all over the racetrack. It's said that each time Porsche tracked down a problem and fixed it, something new went wrong. This character flaw ultimately delayed its deployment in a production car for a number of decades, although that's not to say Porsche didn't try and put the PDK in customers' hands before then. There were several attempts, from a test fitment to a 924S to a production-intent integration of PDK into the 944 Turbo. A 968 equipped with PDK was nearly readied for sale before ZF's Tiptronic [note: automatic transmission] was called in to pinch hit, and a stillborn successor to the 959 (dubbed 969) with PDK was killed a year before going on sale for 1991." "Porsche had limited success on the racetrack with the PDK, as it was very bulky and complicated, with many reliability issues stemming from both the electronic and hydraulic systems. Weissach engineers also installed versions of the PDK in several prototype road cars, but the engineers did not consider it ready for primetime given the limited electronics technology of the day and its lack of refinement for road use."	(Stoklosa, 2013) (Andropoulos, 2015)

Porsche	"PDK? That's Porsche Doppel-Kupplung, or Double-Clutch. Porsche's wizards at Weissach, its technology hot house outside Stuttgart, initiated development for racing in 1982. It hit the tracks in '85 in Porsche's world beating 956/962 Group C and IMSA cars." "Porsche's main vessel of PDK development was the 956/962 endurance race car program of the 1980s. The engineers at Zuffenhausen [Porsche] had been intermittently tinkering with the idea of a fast-shifting dual-clutch automated manual transmission since the 1970s in the form of the Porsche DoppelKupplung, or Porsche dual-clutch transmission. Porsche had limited success on the racetrack with the PDK, as it was very bulky and complicated, with many reliability issues stemming from both the electronic and hydraulic systems. Weissach engineers also installed versions of the PDK in several prototype road cars, but the engineers did not consider it ready for primetime given the limited electronics technology of the day and its lack of refinement for road use."	(Richardson, 2003) (Andropoulos, 2015)
weight disadvantage	"Despite its considerable weight penalty of 88 pounds (which is significant in a sub-2,000-pound race car), the original PDK transmission offered the promise of much quicker gearshifts and lap times."	(Andropoulos, 2015)
economic recession	"Ongoing engine development issues and a projected price of over 200.000 DM in the wake of a recession [i.e. early 1990s recession] kept it from succeeding the 911 turbo. (The 964 turbo made its debut in March 1990.) Fifteen of the 16 prototypes were destroyed in December 1988 and the sole remaining prototype has not been seen since." "Nineteen eighty-eight was the year of dec1sion for the 965 […] company's declining results – hit both by falling sales in the wake of the October 19, 1987 stock-market crash and another precipitous decline of the U S dollar. Sales in America were still welcomed Branitzki said in January, calling the volume losses there "grievous." But regrettably his customers, "the doctors, dentists, lawyers, and NASA engineers in the US were also heavily invested in the stock market. He added that the so-called yuppies are a vanishing minority in our customer base." Branitzki announced cuts in the dividend and in production for 1988 while reminding securities analysts that Porsche was debt-free and had the equivalent of DM370 million ($220 million) in the bank. Porsche still had the money to make decisions and develop cars, but those had to be the right decisions and the right car."	http://en.wikipedia.org/wiki/Porsche_964 (based on Ludvigsen, 2005) (Ludvigsen, 2005, pp. 112–113)
production system	"Instructions were given to scrap 15 of the 16 [sixteen] 965 prototypes and any and all of the special tools that had been prepared for its manufacture."	(Ludvigsen, 2005, p. 116)
technology transfer from Porsche to Audi [note: Audi is part of Volkswagen Group]	"[…] Audi had a direct line to this technology through its then R&D director Dr Ferdinand Piech, part of Porsche's controlling family and designer of the benchmark Porsche 917. So it came to pass that Audi Sport would work with Porsche on development of a PDK 'box for its rally quattros. In the PDK-equipped S1 E2, "I could change gear at full throttle, without any decrease in pulling power or any falling off of turbo boost", recalls Rohrl, tasked with development testing. Those characteristics were key to the PDK's deployment, for Audi Sport needed to raise its game. In 1984, the team had won the Drivers' (Stig Blomqvistl and Manufacturers' World Championships; a year on, the latest evolution of its frontengined, all-wheel drive pioneer was under pressure from the new generation of ultra-light, mid-engined, 4WD Group B cars from Peugeot, Lancia and Austin Rover. […] When, in early November 1985, Rohrl debuted the PDK E2 in the Austrian non-WRC Semperit Rally as a shakedown for the lombard RAC Rally 13 days	http://www.urquattro.fr/Web/Pages/Journaux/diversetrangers/JE08.html

	later, he blitzed the event. Fastest on all 24 stages, he won by 19 minutes. Devastatingly effective, this Audi Sport quattro S1 Evolution 2, numbered RE 02 of 20 examples, registration IN-NY 18, was swiftly reprepared for Britain's WRC round. In August, with a six-speed manual 'box, Stig Blomqvist had taken it to second in the 1000 lakes Rally. […] When we discussed PDK in 1998, Rohrl told me that Audi Sport had only two PDK 'boxes, for selected events. After the lombard RAC, the next PDK appearance was scheduled for the May '86 Acropolis, in his car. He recalled testing RE 02, re-shelled in PDK form, in Greece. Meanwhile, a second PDKcar, RE 1S, was prepared as his rally car. It would never run: after an amateur's Group B car killed several spectators on the Portugal Rally in March, Audi Sport withdrew from Group B World rallying."	
technology readiness	"So, why didn't the PDK appear in street Porsches by the late 1980s? Given the state of the electronic technology then, it would have been prohibitively expensive and likely none too civilized. The early automated-manual gearboxes that appeared in road cars a decade or more after that were none too civilized, either, and had the benefit of much more development in control technology."	http://www.cnet.com/news/porsches-pdk/
electronics	"[…] a very accurate and safe control is needed to achieve both comfort and sporty behavior. For this reason, the commercialization of the Dual Clutch Transmission was reached only 20 years later [researcher's note: i.e. 2000s], when the electronic control of engine and transmission had developed enough."	http://amsdottorato.unibo.it/5683/1/Olivi_Davide_tesi.pdf
FIA racing ban	"There is a downside to the [DSG] gearbox though: it cannot be used in races. This is because it changes gear so quickly, and the loss of drive is so minute, that the gearbox gets classed as a Constantly Variable Transmision. The FIA and other governing bodies outlawed this in the early 80s. However, with the speed that some of the current Formula One cars can now change, this may be altered. The current Honda gearbox is called the 'Lossless' gearbox after all, but they did prove that it reduces engine power and its use was therefore allowed." "[T]win clutches have been banned, anyway, on the grounds that they would constitute a continuously variable transmission (CVT), which is forbidden under F1's technical regulations."	http://blogcritics.org/dsg-the-future-of-the-gearbox/ http://www.formula1-dictionary.net/seamless_gearbox.html
BorgWarner & VW	"The first ever worldwide series production DCT was the Volkswagen Group DQ250[10] six-speed dual-clutch transmission,[8] with dual concentric wet multi-plate clutches. It was produced at the Group's Kassel plant under exclusive license from Borg-Warner for use in transverse powertrain installations, of either front-wheel drive or four-wheel drive (4WD) layouts." "European automobiles equipped with DCTs include the Volkswagen Beetle, Golf, Touran, and Jetta as well as the Audi TT and A3; the Skoda Octavia; and the Seat Altea, Toledo and Leon." "Volkswagen has filed more than 60 patent applications for the DSG which is being built at the company's gearbox factory in Kassel where it has invested € 150 million ($ 172 million) in production facilities capable of outputting 1,000 units per day. The transversely installed DSG gearbox was developed in a copy-book transatlantic partnership between Volkswagen and BorgWarner, a triumph of assiduous cooperation between the VM [vehicle manufacturer] and its Tier I supplier over a period of five years."	http://en.wikipedia.org/wiki/Dual-clutch_transmission http://auto.howstuffworks.com/dual-clutch-transmission3.htm (Stefanini, 2003, p.71)
BorgWarner	"BorgWarner is still the only player in the dual clutch market although other manufacturers are set to enter it. 'Our customers will clearly not allow us to be the only players in this market,' said Matthes. 'But the main competition that is	(Beecham, 2005)

	taking place right now is not so much between us and other players but between the wet clutch technology - which we favour because it is more robust, easier to handle and has a wider application range - and dry clutch technology. […]'”	
faster and more capable electronics	“After renewed interest in the 1980s [2, 3], where the twin-clutch design had been applied to race cars, only the advent of faster and more capable electronics at the end of the 1990s led to full interest from all major car and transmission manufacturers.”	(Goetz et al., 2005, pp. 951–952)
technology barriers	“Serial production of a dual clutch or DSG transmission has been untenable to date due to insufficient means of mechanical (proper clutch actuation requires precise control of the simultaneous engagement and disengagement of the clutches), as well as electronic controls. Audi again proves its technical expertise and prowess by bringing this first-ever commercial application to the streets.”	http://www.audiworld.com/features/tests/2004tt32.shtml
technological advancements	“'The critical piece of engineering is the wet friction (clutch) technology,' says Mr. Welding. He says that BorgWarner's recent advances in friction materials - "We saw this (automated manual market potential) coming a few years ago" - play a vital role, along with high-tech lubricants and the capability of advanced electronic controls. The idea of automated manuals, he reminds, isn't new. But the contemporary developments now make the "idea" customer-ready.”	(Visnic, 2000)
technological advancements: lubrication and friction materials, electronics and solenoid	“Matthes [President and General Manager of Borg Warner Transmission Systems, 2005] believes there were a number of key technology advances which made the production of the dual-clutch transmission possible. He said: 'Let's start with the clutch itself. Over the past few years we have made some major advances to the friction material such as improving heat resistance. Also, there have been improvements in oil which, together with the friction material, provide a system that is more stable under the certain conditions. There have also been some advances with the control module. Over the last decade, the electronic control module has become more powerful and yet cheaper. For the DualTronic we also developed a special type of solenoid for more precise clutch control. So electronics and solenoids on the control side as well as improved friction materials and oil have been the key technology breakthroughs.'”	(Beecham, 2005)
control unit by Continental Automotive Systems	“Continental Automotive Systems developed a control unit for a dual-clutch transmission, which entered production in 2003. In bracing itself for a booming DCT market, the company has further developed its control involving mechanical components based on the automaker [e.g. VW] requirements.” “Meanwhile, Continental Automotive Systems has developed a control unit for a dual-clutch transmission which entered production in 2003. The company is bracing itself for a booming market. "Right now we are running five separate development projects for future automatic transmission. Four of the resultant control units will form part of double-clutch transmissions," said Bernd Stockmann, manager of the company's transmission profit centre within the Chassis and Powertrain business unit.”	(Senatore, 2009, p. 96) (Beecham, 2005)
switching costs	“Europe is the key for a couple of reasons. First, the technology is "particularly attractive for Europe," says Mr. Welding, because inherent in the DCT design is the ability to use large hunks of existing manual transmissions; no lavish or expensive retooling is required for a move to DCT designs. The current manual transmission installation rate in Europe is a hefty 81%, and Mr. Welding says the DCT technology allows OEs to 'take advantage of the manual transmission investment that's already in place.'” “The manufacturing advantage is that you can use the infrastructure that exists around the manual transmission.”	(Visnic, 2000) (Stefanini, 2003, p.70)
geographic customer preferences	“Automated manuals also reconcile two divergent European automotive trends: the drive for increased fuel economy - still most effectively handled by a manual transmission - and European drivers' emerging preference for automatics, as	(Visnic, 2000)

	roads and cities become frustratingly congested. In the U.S., admits Mr. Welding, there's not much advantage, because fuel economy isn't an issue and the industry's manufacturing investment rests almost exclusively in automatics.”	
ease of scalability	“No problems there for DCT, says Mr. Welding. ‘The dual clutch (design) places no special limitations on the gearbox,’ he claims. ‘The DCT approach can be scaled-up to meet any foreseeable application, and there is no torque limitation like there is with the belt-CVT approach.’”	(Visnic, 2000)
cost advantage over typical automatic gearbox	“Mr. Welding confidently predicts that cost will rest somewhere between today's automatics and manuals. When pressed, he says a typical industry cost for an autobox is around $1,000, a manual about $500; he pegs a DCT-outfitted automated manual at $850 to $900, adding that ‘it should be lower-cost than a conventional automatic or a CVT.’”	(Visnic, 2000)
capital cost	“Another hotly debated benefit of the dual-clutch gearbox is capital cost. Some observers liken production costs to a conventional automatic, and a spokesman from Volkswagen has said that its DSG unit actually costs around € 500 ($575) less to produce. As the company ramps up to become the world's only volume producer, it would be difficult to argue that point.”	(Stefanini, 2003)
Ricardo & VW partnership	“On the gearbox side, we have done the same gearbox, though much smaller and lighter, for our ordinary passenger ranges such as the Golf. Here, Ricardo learned from VW concerning some software strategies and so on. So I think we both share a little bit, we both learn a little bit.” (Lewin, 2006, p. 12) “You have to visualize the project as two distinct elements, the first being mechanical and the second the control. For both elements we worked very closely with the VW/Bugatti engineering team to ensure both that they got what they wanted and that we could incorporate their knowledge of specific lessons learned from their own DCT programme in the VW Golf into the programme.” (Lewin, 2006, p. 14)	(Lewin, 2006)
Ricardo & Chrysler collaboration	“We started on the Chrysler ME Four-Twelve dual clutch transmission programme in July of last year [i.e. 2003],” says Lee Sykes, technical director of Ricardo Driveline and Transmission Systems. “The required timescale was extremely compressed but we were fortunate in being able to merge our engineering efforts with an on-going [researcher’s note: hinting here at the Bugatti Veyron DCT transmission] and highly successful internal Ricardo research programme into dual clutch transmission (DCT) technology which was aimed at addressing similar goals to those envisaged by this programme.” (Lewin, 2004, p. 10) “A joint trans-Atlantic programme involving over 30 engineers at Ricardo’s Leamington Spa driveline centre in the UK and their opposite numbers within Chrysler and at the Ricardo Technology Campus in Detroit, the project – codenamed Freeway – officially started on July 1st 2003. (Lewin, 2004, p. 12)	(Lewin, 2004)
Porsche & ZF	“Porsche and ZF have been collaborating on the design and development of these transaxles—code-named the DT11 (PDK) and the MT11 (manual)—since 2003. From the start, the two companies planned on sharing the maximum number of parts and manufacturing tools.”	http://www.caranddriver.com/features/a-tale-of-two-porsche-seven-speeds-manual-and-pdk-tech-dept
Market actors and factors market stabilization phase	Description of their influence or role	Source
accidents or events	“In some cases, the transmissions themselves were their own worst enemies. Early versions in some high-powered performance cars with DCTs were awesome for track days, but brutal in their day-to-day operation. Some, like the	http://gearpatrol.com/2013/08/19/a-guide-to-dual-clutch-

	Smart ForTwo, touted "automated manual" gearboxes but were actually single-clutch versions, which gave the entire genre a bad reputation due to a combination of dull engine and transmission response."	transmissions/
Getrag & Ford	"Ford is the second major manufacturer to commit to dual-clutch transmissions, made by Ford of Europe and its 50/50 joint venture transmission manufacturer, GETRAG-Ford. It demonstrated the Powershift System, a six-speed dual-clutch transmission, at the 2005 Frankfurt International Motor Show. However, production vehicles using a first generation Powershift are approximately two years away."	http://auto.howstuffworks.com/dual-clutch-transmission3.htm
technology license from BorgWarnet to Getrag	"Two Getrag transmissions on display at the 2005 Frankfurt Motor Show this week use BorgWarner's fuel-efficient DualTronic(TM) wet dual-clutch module technology. The programs will start production in 2007 and are for vehicle types that range from compact and mid-sized to luxury passenger cars and sport-utility vehicles. 'We're pleased to announce Getrag as a new customer for DualTronic(TM) transmission technology,' said Tim Manganello, BorgWarner Chairman and CEO."	http://www.prnewswire.com/news-releases/borgwarner-to-supply-dualtronictm-wet-clutch-technology-for-getrag-transmissions-displayed-at-frankfurt-motor-show-54940572.html
Getrag	"Getrag [supplier of transmissions] has developed a complete range of DCT transaxles […]. Getrag will be providing its DCT in its first commercial applications, for the Dodge Journey and Volvo S40 and V50, from mid-2008. Getrag has the 6DCT250 dry DCT under development, for use in front wheel drive transverse applications, and uses electro-mechanical actuation, rather than electro-hydraulic. […] Getrag is also working with Bosch to develop a DCT for use in hybrid vehicles."	https://www.tititudorancea.net/z/dual_clutch_transmission.htm
economic downturn	"In the 2nd quarter of 2008, Getrag had signed an agreement with Chrysler to supply its PowerShift DTCs for use in American markets. However, due to the global economic downturn, this was subsequently cancelled"	https://www.tititudorancea.net/z/dual_clutch_transmission.htm
LuK	"LuK is also working on its dual-clutch transmission solution. The company began work on this area in 2003. LuK refers to it as a 'parallel shift gearbox'. "Depending on the application, we can offer our customers designs for the wet or the dry version," said Dr Wolfgang Reik, head of LuK's R&D department. "On the basis of the development projects underway at present, we believe that the clutch could be part of mass-production by the end of 2007. Although LuK has already shown a dry clutch version of its dual-clutch transmission, the German supplier is keeping its options open. […]" "LuK Clutch Systems, LLC. designed and manufacture the dual dry single plate clutch system for the Volkswagen Group seven-speed DQ200 Direct-Shift Gearbox (DSG) introduced in 2008. This DSG variant is used in smaller cars, with smaller displacement engines with relatively low torque outputs."	http://www.just-auto.com/analysis/european-interest-in-dual-clutch-technology-shifts-up-a-gear_id86405.aspx https://www.tititudorancea.net/z/dual_clutch_transmission.htm
individual transmission solutions	"The main focus of further research has been "individual" solutions tailored to particular uses (see also Chapter 2.5 "Trends in Transmission Design")." (Naunheimer et al., 2011, p. 26) "Despite higher costs in product development and for manufacturing plants, the trend is leading away from the "standard transmission" towards individual solutions. This entails a large number of basic designs and a multitude of adaption alternatives." (Naunheimer et al., 2011, p. 67)	(Naunheimer et al., 2011)
shifting partnership and	"[…] The kind of partnership between the vehicle manufacturer (OEM =	(Naunheimer et al.,

roles of OEM and Tier 1 suppliers	Original Equipment Manufacturer) and the system supplier (Tier 1) is also changing. Vehicles are being equipped with more and more complex functionalities. The increase in function content in the transmission systems and networking with other components of the vehicle lead to changes in the chain of responsibility." "Another trend is that the vehicle manufacturers, who themselves have an increased amount of tasks, expect an ever larger scope of services from their suppliers. The latter have to adapt to new contents. This means, assuming constant resources, that Tier 1 suppliers will themselves pass on tasks and responsibility for certain components to Tier 2 and 3 suppliers [2.13]."	2011, p. 72)
product life-cycle	"Vehicles and transmissions are developed cyclically and have a relatively long product and production lifecycle. Vehicle transmissions generally only require redevelopment after some 10−15 years. The transmission developer must therefore be acquainted with the market situation and be able to assess the market and changing values in society in the long term."	(Naunheimer et al., 2011, p. 41)
technological regime: Diesel engines	"Dual-clutch works particularly well when mated to diesel engines. Because diesels have a narrow rpm band, there are frequent interruptions in the torque flow. A dual-clutch transmission can be shifted without any break in torque flow."	http://europe.autonews.com/article/20050905/ANE/509050838/ford-joins-the-shift-to-dual-clutch-gearboxes

References (excl. direct links)

Andropoulos, C., 2015. The PDK Transmission: How Porsche's quick-shifting PDK works. Excellence.

Beecham, M., 2005. European interest in dual-clutch technology shifts up a gear [WWW Document]. JustAuto. URL http://www.just-auto.com/analysis/european-interest-in-dual-clutch-technology-shifts-up-a-gear_id86405.aspx

BorgWarner, 2014. History [WWW Document]. URL https://www.borgwarner.com/en/Company/History/default.aspx

BorgWarner, 2000. Annual Report 2000 "What's Next."

Diem, W., 2006. Dual-clutch gearbox production rapidly expanding. WardsAuto, Engine Veh. Technol. Updat. 32, 3–4.

Goetz, M., Levesley, M.C., Crolla, D.A., 2005. Dynamics and control of gearshifts on twin-clutch transmissions. Proc. Inst. Mech. Eng. Part D J. Automob. Eng. 219 , 951–963. doi:10.1243/095440705X34720

Lewin, T. (Ed.), 2006. Bugatti Veyron Special. Ricardo Q. Rev. Q2 8–15.

Lewin, T. (Ed.), 2004. Chrysler's supercar sensation. Ricardo Q. Rev. Q4 9–13.

Ludvigsen, E. (Ed.), 2005. 969: The Turbo That Never Was. Excellence 111–116.

Naunheimer, H., Bertsche, B., Ryborz, J., Novak, W., 2011. Automotive transmissions: Fundamentals, Selection, Design, and Application, 2nd ed. Springer, Heidelberg Dordrecht London New York. doi:10.1007/978-3-642-16214-5

Radu, M., 2014. Volkswagen Group's DSG Gearbox Explained [WWW Document]. AutoEvolution. URL http://www.autoevolution.com/news/volkswagen-group-s-dsg-gearbox-explained-88928.html# (accessed 4.1.15).

Richardson, C., 2003. Inspiration for Audi’s new Direct Shift Gearbox came from the double-clutch PDK box developed in Waiter Rohrl's awesome Evolution 2 quattro. Audi Mag.

Russ, C., 2008. Porsche’s PDK: A quick look at the history and technology behind Porsche's new double-clutch gearbox [WWW Document]. CNET. URL http://www.cnet.com/news/porsches-pdk/ (accessed 5.20.04).

Scoltock, J., 2012. Adolphe Kégresse developed the dual-clutch transmission [WWW Document]. Automot. Eng. URL http://ae-plus.com/milestones/adolphe-kgresse-developed-the-dual-clutch-transmission (accessed 4.1.15).

Senatore, A., 2009. Advances in the Automotive Systems: An Overview of Dual-Clutch Transmissions. Recent Patents Mech. Eng. 2, 93–101. doi:10.2174/2212797610902020093

Stefanini, S., 2003. Shift in power to the gearbox. Automot. Manuf. Solut. 70–73.

Stoklosa, A., 2013. Shift This: A History of Porsche’s Sportomatic, Tiptronic, and PDK Transmissions [WWW Document]. Car Driv. URL http://blog.caranddriver.com/shift-this-a-history-of-porsches-sportomatic-tiptronic-and-pdk-transmissions/ (accessed 4.1.15).

Visnic, B., 2000. Tech & Trends. WardsAuto.

Volkswagen AG, 2009. Annual Report 2008. Wolfsburg, Germany.

Volkswagen AG, 2008. Annual Report 2007. Wolfsburg, Germany.

Volkswagen AG, 2007. Annual Report 2006. Wolfsburg, Germany.

Volkswagen AG, 2005. Annual Report 2004. Wolfsburg, Germany.

Volkswagen AG, 2004. Annual Report 2003. Wolfsburg, Germany.

3. Pattern

3.1. Pattern data

Date	Remarks	Source
1908	"In 1908, for example, J.E. Francis introduced his 'Slip Prevention Regulator for Rail Vehicles'."	(Lawes, 2014)
1908	"The idea of a device for preventing wheel blocking had been formulated as early as 1908. This was the year in which the Briton J.E. Francis presented his "slip-prevention regulator" for rail vehicles, to avoid wheel-slip during braking. But all early attempts to master wheel blocking were doomed to failure: Karl Wessel's "brake-power regulator" was as ineffective as Werner Möhl's "safety device for hydraulic brakes" and Richard Trappe's "brake-blocking preventer", so that the 1941 Handbook of Automobile Technology could only summarize the situation thus "Attempts to combat the danger of blocked brakes by means of devices have, so far, only achieved very modest success.""	(Robert Bosch GmbH, 2003a, p. 31)
1920	"In 1920 Gabriel Voisin experimented with a system that modulated the hydraulic braking system pressure on his aircraft brakes to reduce the risk of tyre slippage, something the high pressure and low contact patch aircraft tyres suffered from terribly."	(Lawes, 2014)
1928	"The first proper recognition of the ABS system came later with the German engineer Karl Wessel, whose system for modulating braking power was officially patented in 1928. Wessel, however, never produced a working product and the patent concept was as far as the system went."	(Lawes, 2014)
1928	"As early as 1928 the German Karl Wessel had been granted a patent on a braking force regulator for automobiles, but this design only existed on paper."	(Daimler Communications, 2008)
1929	"ABS was foremost elaborated for airplane employ in 1929 by the French car and airplane trailblazer Gabriel Voisin, as brink decelerating on aircrafts is almost not possible."	(Levine, 2014)
1936	"Bosch filed a patent application for an "Apparatus for preventing lock-braking of the wheels of a motor vehicle" as early as 1936."	(Robert Bosch GmbH, 2003b)
1936	"Eight years later [i.e. 1936] Robert Bosch's engineering company produced a similar patent, but again the system did not go beyond the concept stage."	(Lawes, 2014)
1940	"Vehicle brake control means […] [researcher's note: perhaps the basis for the Decelostat] […] Publication number US2218619 A; Publication date Oct 22, 1940; Filing date Aug 31, 1939; Inventors Mcneal Donald L; Original Assignee Westinghouse Air Brake Co […] This invention relates to vehicle brake control […] and further characterized by means for effect a rapid release of the brakes on a vehicle insuring a reapplication of the brakes after the 'wheel that begins to slip so as to prevent […]"	http://www.google.com/patents/US2218619
1939-45	"Many technological advances were accelerated by the outbreak of the Second World War, but the production of ABS […] was largely marginalized."	(Lawes, 2014)
1940s	"It is perhaps of interest to recall that the basic idea of what was then called an anti-skid control was first employed for railway braking systems by the Westinghouse Air Brake Company in America, but it was in the further development of this idea and its application to the disc brakes of aircraft that this same company found the widest demands in the late 1940s."	(Nunney, 1992, p. 572)
1941	"In 1941, an anti-lock regulator was tested with which, however, "only modest successes were achieved," as the "Automobiltechnisches Handbuch" (Automotive Engineering Manual) reported. Nevertheless, these first attempts set the course: an anti-lock braking system had to	(Daimler Communications, 2008)

	have sensors for measuring the speeds of each front wheel, as well as a control unit for recording and comparing the data measured by the sensors. This control unit was to correct excessive deviations by individually controlling the brake pressure at every wheel up to the point at which the wheel is about to lock."	
1946	"Crane started the antiskid industry in 1946 with development of the Hydro-Aire Hytrol Mark I antiskid system for the Boeing/USAF B-47. From that initial installation, Crane has continuously designed and developed more refined and sophisticated, high performance analog (Mark II and III), digital (Mark IV) and brake-by-wire (Mark V) systems for the majority of the world[']s aircraft fleets."	http://www.craneae.com/AboutUs/Hydro-Aire.aspx
1947	"Hydro-Aire and Boeing pioneered brake control in 1946 and installed the first system on a Boeing/USAF B-47 in 1947. The B-47 was the world's first high speed, swept wing, jet bomber […] Hydro-Aire has continued to define and refine the science of antiskid brake control since 1947. The systems have evolved from the early tire-savers to the modern, fully adaptive, digital Mark IV system, which is standard equipment on all current production Boeing aircraft."	http://www.craneae.com/Products/Landing/BrakeControlCommercial.aspx
1947	"The first Hydro-Aire Mark I antiskid was developed for the military Boeing B-47 bomber in 1947. Military aircraft received the benefit of the significant performance improvement available from the Hydro-Aire Mark III slip velocity control with systems installed on the F-4, F-15, F/A-18, C-9B, C/KC-135, and the B-1A /B. Developmental Mark III systems were also developed for the F-5 and CF-5 aircraft."	http://www.craneae.com/Products/Landing/BrakeControlMilitary.aspx
1947	"Military Aircraft, with their unique environmental and operational requirements, have always been a significant element of Hydro-Aire's antiskid business. The first Hydro-Aire Mark I antiskid was developed for the military Boeing B-47 bomber in 1947."	http://www.aerospaceonline.com/doc/military-aircraft-brake-control-systems-0001
1948	"While not a fundamental part of the brake equipment, the DECELOSTAT controller is a recommended anti-wheel slip device that modifies the braking force to avert wheel sliding. Its function is to maintain high over-all train retardation by anticipating wheel sliding and momentarily moderating the braking force so that it does not exceed the lowered rail-wheel adhesion existing when wheel slipping occurs. If a wheel slips, the braking pressure is softened and then restored to the value of existing on the other cars of the train. The operating cycle provides instant moderation – the reduction requires less than a second – followed by a fast but controlled build-up of pressure [note: confirming the claims that the pressure was released and then restored, rather than modulated until wheel slip would no longer occur] to that existing on the remainder of the train. If the low adhesion condition persists, the DECELOSTAT controller repeats its function with each wheel slip. "	http://rpca.com/pdfs/Heritagefleetairbrake.pdf
1948 [filed in 1944]	"[Patent for] Deceleration control apparatus US 2447710 A […] Original Assignee Westinghouse Air Brake Co. […]"	http://www.google.com/patents/US2447710
1948 [filed in 1944]	"The Decelostats or wheel slip detectors 9 may be of the rotary inertia type disclosed in the copending application Serial No. 533,284 of Joseph C. McCune and George K. Newell, filed April 29, 1944, [see above]"	http://www.google.st/patents/US2438423
early 1950s	"By the early 1950s similar anti-skid controls, such as the Dunlop Maxaret, were also being developed for the aircraft industry. So it was as a result of the experience gained in this field that the possibility of adapting the Maxaret system for use on motor vehicles was investigated by the Dunlop company and an installation tested by the Road Research Laboratory."	(Nunney, 1992, p. 572)
1951	"In 1946, for example, the platetype brake succeeded the drum type, and five years later came the Maxaret anti-skid unit to increase its efficiency still further; complete pneumatic systems for aircraft were produced;"	(Smith et al., 1961, p. 160)
1951	"Founded in 1943 as Hydro-Aire, Inc., Crane Aerospace & Electronics' location in	http://www.craneae.com/Pr

	Burbank, California made a name for itself by revolutionizing the way antiskid braking was accomplished on commercial and military aircraft. The first Hydro-Aire Mark I antiskid system was fitted on the B-47 military airplane. Hydro-Aire, Inc. was acquired by Crane in 1951 and has been a key part of the business since."	oducts/Landing/LandingSystems.aspx
1951	"THE CONVAIRLINER 340 [note: civil aviation] COINCIDENT with the announcement that United Airlines have ordered 30 of the new Convairliner 340s, the Consolidated Vultee Aircraft Corporation has disclosed details of the performance and general arrangement of this type, which is an improved and enlarged version of the 240-A. […] The landing gear, also, is completely new and will incorporate a Decelostat unit to extend tyre-life by preventing skidding. […]The 44-seot layout of the new Convairliner 340 […]"	(Smith and King, 1951)
1951	"British Messier, Ltd., Cheltenham Road East, Gloucester (Stand 138), will exhibit two large units in the shape of the main bogie undercarriage (less wheels) for a new bomber, and a smaller display for the Bristol 175 airliner. A sectioned model of the Westinghouse Decelostat (in which British Messier have collaborated) will also be shown, together with Perspex dynamic models of the pump, hydraulic motor, and electro-selector of the company's 4.000 lb/sq in hydraulic system."	http://www.flightglobal.com/pdfarchive/view/1951/1951%20-%201785.html
early 1950s	"Decelostat which, made by Westinghouse Brake and Signal Co., Ltd. […] is the British version of an American development. The common foundation and technical liaison existing between the Westinghouse Brake and Signal Co., Ltd., in Great Britain, and the Westinghouse Air Brake Company in America, have made it possible for Decelostats to be made available—at Ministry of Supply request—for trials over here."	http://www.flightglobal.com/pdfarchive/view/1951/1951%20-%200265.html http://www.flightglobal.com/pdfarchive/view/1951/1951%20-%200266.html
(presumably) 1950s	"The Maxaret system pioneered by Dunlop was used in initial tests on the CF-100 Canuck, a jet aircraft made by Avro […]"	(Lawes, 2014)
1952	"However, the transfer of the idea into hardware for use on the road proved to be significantly more difficult than expected. The sensors did work satisfactorily as early as 1952, in an anti-skid system for aircraft, […]	(Daimler Communications, 2008)
1952	The Dunlop "Maxaret" anti-skid unit was first made available to the aircraft industry in 1952, and was developed to ensure that optimum braking power can be applied in all conditions of weather and runway, without wheel-lock and skidding resulting."	http://www.jcc.ch/fileadmin/user_upload/Jensen_Modelle/FF/Broschueren/FF_ABS_67.pdf
1952	"Nevertheless, the idea to make cadence braking automatic has existed for several decades, and eventually led to the development of the antilock braking systems (ABS). The first system able to prevent wheels from being locked under conditions of excessive braking was the 1952 Dunlop Maxaret. This system, which was totally mechanical, was applied to an aircraft rather than a car, but represents the first commercial application of the invention."	(Veloso and Fixson, 2001, p. 248)
1952	"The Maxaret is but one of several such devices now available which are likely to see ever-increasing use on tandem undercarriage layouts, such as those on the Boeing B-47 and B-52 jet bombers, and on braked bogie units. […] The devices do not, however, as is commonly supposed, reduce tyre wear. […A]s the brakes are working at maximum efficiency, the tyres are doing the maximum amount of work and are actually at the point of incipient skid throughout the landing run and tread wear is thus increased. London, S.E.19. MAURICE F. ALLWARD. In expressing his views, Mr. Allward does not mention that "Maxaret" is a Dunlop development. A similar device is the Westinghouse "Decelostat."—Ed."	http://www.flightglobal.com/pdfarchive/view/1952/1952%20-%203059.html
1952	"[…] and Dunlop (Canberra wheel with plate brake and an example of the Maxaret installation). Th e other British anti-skid device, the Decelostat, is under development; it was shown in its latest form on the Westinghouse stand."	http://www.flightglobal.com/pdfarchive/view/1952/1952%20-%202780.html
1953	"Messier.—The largest exhibit by this famous undercarriage maker was the main leg for the Nord 2501 which was an all-steel welded unit with an excellent finish. […]A	http://www.flightglobal.com/pdfarchive/view/1953/1

	particularly interesting development was the new anti-skid device which is being marketed under the name of Ministop. The device consists of an accelerometer—a free mass rotating with the wheel—together with a centrifugal governor and an associated electrical circuit. The general principle of operation is very similar to that of both the Dunlop Maxaret and the Westinghouse Decelostat and extensive testing in a MD 315 aircraft under French government supervision has given favourable results. We were told that the Ministop would be produced in this country by the British Messier, Ltd" "[…] known and practical brake control systems, such as the Ministop anti-skid system of the Gruen Watch Company"	953%20-%200927.html https://www.google.com.ar/patents/US2957658
1953	"The Maxaret, a small unit weighing 4.7 lb, is introduced into the hydraulic brake circuit. No major modification is necessary as it can be mounted on the brake torque plate or any convenient structural member. Each unit comprises a sensitive valve mechanism controlled by a small flywheel assembly housed in a rubber-tyred shell, and provision must be made for this shell to be rotated by direct contact with the rim of the landing wheel. The Maxaret unit is coupled into the normal brake feedline, the only additional piping necessary being from an exhaust connection to the hydraulic return line. […] Immediately after touch-down the pilot can apply full braking pressure in the knowledge that any tendency to wheel locking due to lack of weight on the wheels will be counteracted automatically. […]Following exhaustive laboratory testing, hundreds of landings were made with Maxarets on a D.H. Devon (converted to hydraulic braking) and a Handley Page Hermes V. Some very considerable and satisfactory experience with the units has subsequently been obtained on a number of the latest types of service aircraft, including the English Electric Canberra, the Handley Page Victor, Avro Vulcan and Avro Canada C.F. 100, and the Short and Harland S.A.4. After successful trials made under the severest airline operating conditions, Maxarets are now being specified for Comets and Viscounts."	(Smith and King, 1953, p. 587)
1954	"Now standard equipment on most of Britain's 'superpriority' Service types, as well as on the most famous Civil aeroplanes, the Dunlop Maxaret Anti-Skid Unit is clearly the greatest advance in aircraft braking since the plate brake. It is simple . . small . . . compact . . . superbly efficient. […] Practical tests on many different types of aircraft have proved that the Maxaret actually reduces landing runs up to 30%. The military advantages of this advance are obvious. On Civil aircraft it means—chief amongst many other things—more profitable permitted payloads."	(Smith and King, 1954)
1954	"The sensors did work satisfactorily as early as 1952, in an anti-skid system for aircraft, and in 1954 in a Knorr braking system for railways."	(Daimler Communications, 2008)
late 1950s	"The potentialities of antilock braking were demonstrated in the late 1950s with the largely mechanical Dunlop Maxaret system when it was tried on cars in Britain with the help of the Road Research Laboratory, after being proved on aircraft some years before."	(Curtis, 1971, p. 358)
1958	"In 1958, Road Research Laboratory tested the ABS system on a Royal Enfield Super Meteor motorcycle. The application was made to motorcycles because slipping or skidding out is such a common cause of accidents for bikes. The manufacturer noted the improvement, but did not decide to produce ABS-equipped bikes in manufacture."	http://mastermuffler.net/abs-brakes-gabriel-voisin/
1958	"In 1958, a Royal Enfield Super Meteor bike was applied by the Transport Research Laboratory | Road Research Laboratory to trial the Maxaret Anti-lock brake. The trials revealed that Anti-lock brakes may be of significant worth to motorbikes, for that skidding is included in an elevated dimension of mishaps. […] Enfield's technological director at the time, Tony Wilson-James, saw itty-bitty time to come in	(Levine, 2014)

	configuration, nevertheless, and it was not set in to manufacture by the corporation."	
1958	"[T]he factory also loaned a Super Meteor to the Road Research Laboratory for development work on anti-lock brakes based on the Maxaret system that had been proved on the Ferguson racing car. But Tony Wilson-James, technical director, saw little […]"	(Reynolds, 1990, p. 121)
1958	"WHEN a Jaguar car, equipped with a Dunlop Maxaret anti-skid braking system, was demonstrated in 1958 on the proving ground of the Dunlop Rubber Co. Ltd., Fort Dunlop, Birmingham, the purpose of the organizers was to show that prevention of wheel locking would ensure that the vehicle did not develop a tail swing when the brakes were fully applied on a slippery surface and that the stopping distance would be materially reduced. The Maxaret principle was applied to hydraulically actuated disc brakes on all the wheels and the system was generally similar to that used successfully on aircraft for some years."	(Commercial Motor, 1966a, p. 100)
1959	"Kelsey Hayes develops the speed sensor later used in cruise control and anti lock braking systems (ABS)"	http://www.britishcarcouncil.com/history/lucas.html
1960s	"Anti-lock braking systems were first developed for aircraft. An early system was Dunlop's Maxaret system, introduced in the 1950s and still in use on some aircraft models. This was a fully mechanical system. It saw limited automobile use in the 1960s in the Ferguson P99 racing car, the Jensen FF and the experimental all wheel drive Ford Zodiac, but saw no further use; the system proved expensive and, in automobile use, somewhat unreliable. However, a limited form of anti-lock braking, utilising a valve which could adjust front to rear brakeforce distribution when a wheel locked, was fitted to the 1964 Austin 1800 [researcher's note: the system on the Austin 1800 does not entirely classify as ABS, since it adjusted the brake force distribution –front to back– and not directly the actual brake pressure applied to the skidding wheel]."	http://www.motorcars.in/brakes/abs.htm
1960s	"In the 1960s, an experimental all-wheel-drive Ford Zodiac, and two other high-performance cars, the Jensen FF and the Ferguson P99, were built with full mechanical ABS. However, the system was not built well and was ineffective and costly."	http://mastermuffler.net/abs-brakes-gabriel-voisin/
1960s	"A completely automatic configuration saw restricted car employ in the 1960s in the Ferguson P99 rushing automobile, the Jensen FF, and the new altogether Ford Zodiac [note: the luxury version of the Ford Zephyr], however saw no additional use; the configuration demonstrated costly undependable."	(Levine, 2014)
n.d.	"This unit [i.e. Dunlop's Maxaret system] is now fitted to the Jensen FF (Ferguson Formula) as part of the four-wheel drive package designed by Harry Ferguson Research Ltd. […] The Ferguson Formula uses a single Maxaret unit controlling a double-sided vacuum servo, which applies and releases the otherwise normal brakes. […] The great disadvantage of the complete Ferguson Formula system, however, is its bulk, weight and cost – factors which add up to make it an extremely unlikely candidate for fitment to small cars, even though GKN has bought the manufacturing rights with the long-term objective of volume production. But in all countries with severe winters, it would be a worthwhile option for the more expensive saloons, and for powerful American cars which are generally handicapped by poor traction and adhesion on snow and ice."	(Curtis, 1971, p. 359)
1960s	"[note: the system on the Austin 1800 does not classify as ABS, since it adjusted the brake distribution and not the brake pressure] A fully mechanical [ABS] system saw limited automobile use in the 1960s but saw no further use as the system proved expensive and, in automobile use, unreliable. A limited form of manual anti-lock braking was fitted to the 1964 Austin 1800, with other crude systems entering limited production in the 1970s."	http://www.roadsafe.com/magazine/2008spring/abs.htm
n.d.	"If the speed-friction characteristics of, say, a brake block rubbing against the tyre	(Barwell, 1973, p. 151)

	could be made always equal to those of the tyre running on the track, the former could be used as a "phantom" or "analogue" of the latter so as to operate the appropriate controls. Figure 13.3 shows a system, originally introduced by Messrs. Dunlop whereby a monitoring shoe is used both to measure friction and to operate the main brake."	
1960s	"The foremost belated microelectronic against bolt configuration was elaborated in the belated 60s for the Concorde airplane."	(Levine, 2014)
1963-68	"The first well-known antiskid unit in this country [i.e. US] was invented by Frank Perino, who formed Perma Research and Development Co. to market it. The "brain" of this device was a gyro that spins exactly seven times as fast as the wheel spins [note: i.e. mechanical]. […] Perma's unit has been demonstrated to automakers periodically over the past five years [i.e. 1963-1968, the former being the publication date of the source], but it never was accepted because it never quite lived up to its promises."	(Cutter, 1968, p. 206)
1964	"Fundamental research work on the problem [i.e. electronically controlled ABS systems] had begun here [i.e. at Teldix GmbH] as early as 1964. It was realized that while electronically controlled anti-blocking systems were feasible, their development involved such immense financial investment that their use was virtually limited to aircraft and express trains. The cost of the basic electronics needed for an efficient system, however, had to be tailored to the equipment's use in series-production vehicles, and it was thanks to the availability if integrated circuits from the 1964 on. Only two years later, prototypes were already able to cut braking distances."	(Robert Bosch GmbH, 2003a, pp. 31–32)
1964	"From 1964 on, researchers at Teldix GmbH had been working on an antilock system for vehicles. The idea was presented to Daimler-Benz AG in 1966 […]"	(Kuhlgatz, 2014, p. 55)
1965	"Antiskid next bobbed into public view in 1965 on the expensive British Jensen FF equipped with a Dunlop Maxaret unit converted from an aircraft system. Shortly after the Jensen's introduction, Ford Motor Co. started a hard drive toward antiskid. During the past summer, Ford staged an informal antiskid competition asking all interested suppliers to demonstrate their hardware. Among the auto supplier[s] demonstrating devices to Ford were Kelsey-Hayes, Bendix, TRW (formerly Thompson-Ramo-Woolridge) and Eaton, Yale and Towne, as well as two British brake suppliers Lockheed and Dunlop. Two Ford groups – Ford Research, and Ford Transmission and Chassis Division – have systems. Goodyear also has a system."	(Cutter, 1968, p. 206)
n.d.	"The P99 was extensively tested using the Dunlop system in place, but when the governing body introduced a rule changing the engine capacity by a considerable margin, the P99 was suddenly too heavy for its own good. Something had to go, and as a result the P99 only ever raced without its Maxaret system fitted."	(Lawes, 2014)
1966	"The first road vehicle antilock braking system to be put into production in Europe was the Dunlop Maxaret 'anti-skid' device, a mechanical system fitted to a Jensen car in 1966."	(Day, 2014, p. 386)
1966	"In 1966, however, Jensen fitted their powerful FF, a variant of the Interceptor utilizing a Ferguson four-wheel drive system, unheard of in cars of the time, with the Maxaret system. This made it one of the most technologically advanced car of its era, but the Jensen was still very much a low volume car."	(Lawes, 2014)
1966	"[T]he Dunlop Maxaret anti-lock principle was eventually adapted to the braking system of the specialist Jensen FF four-wheel-drive car in 1966 […]"	(Nunney, 1992, p. 572)
1966	"From 1964 on, researchers at Teldix GmbH had been working on an antilock system for vehicles. The idea was presented to Daimler-Benz AG in 1966, and close collaboration between the two companies ensued. Comprehensive winter trials demonstrated that the product (known as ""ABS 1") worked, but the durability of its electronics left a lot to be desired."	(Kuhlgatz, 2014, p. 55)
mid-	"A much simpler system, requiring only one Maxaret unit to operate all four wheels,	(Starks, 1968, p. 9)

1960s	has recently been produced (Bulmer 1966). This is the four-wheel drive car (the Ferguson car) with novel transmission and brakes. Trials with the racing car version of this car equipped with the Maxaret anti-locking device have been carried out by the Laboratory, in collaboration with the manufacturers, to study the performance of the anti-lock braking system at speeds up to about 140 m.p.h."	
1966	"From 1964 on, researchers at Teldix GmbH had been working on an antilock system for vehicles. The idea was presented to Daimler-Benz AG in 1966, and close collaboration between the two companies ensued. Comprehensive winter trials demonstrated that the product (known as "ABS 1") worked, but the durability of its electronics left a lot to be desired."	(Kuhlgatz, 2014, p. 55)
1966	"Dunlop Maxaret anti-skid braking system, was demonstrated in 1958 on the proving ground of the Dunlop Rubber Co. Ltd., Fort Dunlop, Birmingham, the purpose of the organizers was to show that prevention of wheel locking would ensure that the vehicle did not develop a tail swing when the brakes were fully applied on a slippery surface and that the stopping distance would be materially reduced. The Maxaret principle was applied to hydraulically actuated disc brakes on all the wheels and the system was generally similar to that used successfully on aircraft for some years. On Monday of this week [issue from 16th of September 1966] a Maxaret system was demonstrated on the same proving ground, but this time applied to the air-pressure brakes on the driving axle of a Leyland Beaver tractive unit hauling a laden Crane Fruehauf single-axle semi-trailer, and the purpose of the demonstration was to show that this use of the system eliminated jack-knifing. The front brakes of the unit had been made inoperative to increase jack-knifing tendencies, and the vehicle was braked on the skid patch at 25 m.p.h. on several runs with and without the Maxaret in service. Without the Maxaret working the vehicle jack-knifed to the limit of articulation and with the Maxaret it was brought to rest in a straight line."	(Commercial Motor, 1966a, p. 100)
n.d.	"Recent advances in the brake design field have led to the application of the "Maxaret" aircraft system to road vehicles. […] If the wheel locks, the flywheel continues to turn and, overcoming the resistance of the clutch, opens a pressure valve which releases the brake. There are other systems using anti-lock devices, one of which is governed by a pendulum which takes into account vehicle attitude at any instant and slightly releases any brake about to cause wheel lock, and hence the brakes can be fully applied without danger of this occurring."	(Hobbs, 1979, p. 295)
1966	"The first of 12 Shell-Mex and BP articulated road tankers to be fitted with the Dunlop Maxaret braking system was handed over on Monday to Mr. F. K. Farquharson, manager, road and rail equipment, Shell-Mex and BP Ltd., by Mr. Peter Ware, manager of the product development division of Dunlop, Coventry. This was followed by a demonstration on the Dunlop "proving" ground of the tanker, a tandem-axle outfit with a Scammell Highwayman normal-control tractive unit and Thompson Bros. 4,000 gal. tank. Also demonstrated were a Leyland Beaver/Crane Fruehauf three-axle articulated outfit. Both were braked from around 22 m.p.h. on the skid patch with and without the Maxaret in operation (on the driving axle). The first test of a Maxaret applied to the driving axle of the tractive unit of an artic was described in the September 16 issue of COMMERCIAL MOTOR, the object of all the tests being to show that use of the Maxaret eliminated jack-knifing. In the case of the tanker, the wheels of the trailer axles locked when the brakes were applied, and although the outfit did not jackknife there was a pronounced trailer swing as the vehicle came to rest. […] When outlining the development of the system, Mr. Farquharson envisaged the possibility of applying an anti-locking system in due course to' all the wheels of the vehicle, and in answer to a question after the demonstrations, a Dunlop production	(Commercial Motor, 1966b, p. 41)

	engineer said that initially a batch of 500 Maxaret units would be manufactured. Full-scale production would probably be started in about two years' time following further development and refinement."	
1966	"Anti-skid brakes first turned up on aircraft in the late 1940s. One of those purely mechanical systems, Maxaret, was adapted to the British Jensen FF, a four-wheel-drive version of the company's Interceptor grand touring coupe, in 1966. Just 320 FF models were built through 1971, and this right-hand-drive-only model was not exported (officially) to the U.S."	(Koscs, 2013)
n.d.	"One of the outstanding features of the newly announced Jensen 'FF' (Ferguson Formula) saloon is the incorporation of the Dunlop – Ferguson anti-skid braking control system in this radical four-wheel-drive model. Jensen are the first manufacturer to offer a production car with this braking system. Not only does its use resist wheel-lock, but it also increases driver control and directional stability during heavy braking"	http://www.jcc.ch/fileadmin/user_upload/Jensen_Modelle/FF/Broschueren/FF_ABS_67.pdf
1967	[referring to Dunlop Co Ltd] Foleshill] Landing gears: […] rim and axle-mounted versions of the Maxaret anti-skid system; and the Mk 10 Maxaret electronic/ hydraulic adaptive system produced under collaborative licence from the Hydro-Aire Division of Crane Corporation, USA.	(Smith et al., 1967, p. 847)
1967	The problem [i.e. ABS for cars] was tackled not only by Daimler-Benz engineers but also at TELDIX GmbH in Heidelberg. The two companies did not make any headway with mechanical sensors, so they had to look for another, new solution. In 1967, they came up with a solution to the problem in a joint effort – in the form of contactless speed pickups which operate on the principle of induction. Their signals were to be evaluated by an electronic unit which controlled brake pressure via solenoid valves. At the time, electronics still worked on the basis of analogue technology which was relatively susceptible to failure and consisted of complicated circuitry. Integrated modules did not yet exist. And yet, this proved to be a first, promising approach. For this reason, Daimler-Benz introduced this first generation of an anti-lock braking system for cars, trucks and buses to the public on the test track in Untertürkheim on December 12, 1970 – with a resounding echo by an enthusiastic expert world and press. The principle had been found to be convincing."	(Daimler Communications, 2008)
1968	"TRW acquired Ehrenreich and Cie., a German producer of steering systems which strengthened TRW's position in Germany. The same year, TRW introduced the electronically controlled anti-lock braking system for the Lincoln Mark IV [researcher's note: year of introduction not corroborated by other sources, therefore dismissed]"	http://www.britishcarcouncil.com/history/lucas.html
1968	"By using electronic skid-sensing, the Dunlop Co. Ltd., Coventry, says it has both improved the performance and lowered the cost of its Maxaret anti-skid system for air-braked commercial vehicles. But it will not he generally available until late in 1969. A number of operators' vehicles are being equipped with pre-production sets of the latest Maxaret, and full-scale production will not start until the results of these operational trials have been declared satisfactory. […]"The response is now virtually instantaneous," said Mr. Ware, "being just a few milliseconds. The Road Research Laboratory has completed an intensive two-week proving programme on a Leyland Beaver articulated lorry equipped with the electronic Maxaret, testing at speeds up to 60 mph, which is the fastest that any truck skid-testing has yet been done by the Laboratory. It is reported that the artic remained stable on every test that the Laboratory put it through, including maximum braking on alternate wet and dry surfaces and surfaces wet on one side of the vehicle and dry on the other. In its latest form the Maxaret is expected to cost only about £60 to operators.. The	http://commercial-motor.archive.netcopy.co.uk/article/27th-september-1968/52/cheaper-and-better-maxaret

	previous model cost £120."	
1968	It was just one of the thousands of such stops that have been made at the Bendix Automotive Development Center in South Bend, Ind., as they try to perfect anti-skid devices. The Brake and Steering Div. of Bendix Corp is one of about 10 automotive suppliers, as well as Ford Motor Co. and General Motors, who are engaged in a multimillion-dollar competition to produce the first workable and economical antiskid system for cars. […] Barring serious complications, at least two 1970 cars are expected to have antiskid devices (or "skid control" units, as the more conservative engineers prefer to call them). […] Bendix is also working overtime on a very exotic "full-power" antiskid in which hydraulic force, instead of vacuum, power the antiskid unit as well as the regular brakes.	(Cutter, 1968, pp. 104–105)
1968	"Kelsey-Hayes Co., an auto supplier headquartered in Romulus, Mich., has taken a proven aircraft antiskid system and has rather quickly converted it into a relatively simple – but still electronic – automobile unit. Kelsey-Hayes has built more than 100 prototypes that are now being tested by automakers. And, importantly, the engineers already have data on this technically tricky mechanism based on more than 10,000 instrumented stops. Developed originally by Boeing Aircraft, the Kelsey-Hayes system works on the 15 percent slip idea. Its sensor at the rear wheel reports the rate the wheel is accelerating or decelerating. If the wheel begins to decelerate too rapidly, a small computer "tells" the vacuum-powered brake control to release the brakes briefly. This continues until the vehicle stops. Kelsey's system is fundamentally a rear-wheel unit. Kelsey's engineers feel it's most important to move into this field slowly with a simple, low-priced system that will prevent rear-end slewing. By contrast Bendix thinks that the front-end antiskid should be included in the system because it would provide the all-important steerability and because most of the braking in a panic stop is done by the front brakes."	(Cutter, 1968, p. 206)
1969	The Dunlop Maxaret Mk. IIE electronic anti-wheel-locking device is now available for fitting to tractive units, it was announced at a Press conference on Tuesday. As an original-equipment kit, the Mk. IIE will cost £120, while an existing vehicle can be converted at a cost of £172, the labour time required being 24 hours, which includes testing. Conversions will be performed by teams of Dunlop technicians on operators' premises, and facilities are available to convert 20 vehicles a week at the factory. Production is currently 100 sets a week and will be increased to 400/500 sets a week in the next two years. An exchange scheme will cater for the replacement of faulty units within 24 hours. Around 100 vehicles have been equipped with the Mk. II E over the past 18 months, and the first of these has been covering 1,200 to 2,000 miles a week. Some sets have been in operation for 50,000 miles. It is reported that sets have been ordered for a number of fleets. As reported in CM last week the Mk. IIE device won the Institute of Automobile Assessors 1969 merit award.	(Commercial Motor, 1969, p. 42)
1969	"Engineers recognized that an effective automotive anti-skid system would need to have fast-acting electronic controls. Ford introduced the electronically controlled Sure-Track anti-skid system, developed by Kelsey-Hayes, for the Thunderbird and Continental Mark III in late 1969 for about $195. The Ford Sure-Track system, which worked only on the rear wheels, was made standard for the 1974 Continental Mark IV."	(Koscs, 2013)
1969	"Start of development of antilocking system at Bosch"	(Kuhlgatz, 2014, p. 54)

1969-70	"All Mark IIIs had front disc/rear drum brakes, even with the optional Sure-Track system. Four-wheel discs became standard on the Continental Mark IV in 1976. […] While the Lincoln Continental Mark III would never have anything to rival the Cadillac Eldorado's then-novel front-wheel drive, the Mark III did introduce a significant mechanical innovation of its own: anti-lock brakes. Sure-Track became optional on both the Thunderbird and Continental Mark III in 1969. On the Mark, it cost an extra $195.80 and included a heavier ring gear for the rear differential (which might otherwise be damaged by the judder of the system's operation). It worked reasonably well, although it was not a dramatic improvement over Lincoln's standard brakes, which already incorporated a proportioning valve to limit pressure to the rear drums in hard stops. Front lockup could still be a problem in panic situations, however, and of course Sure-Track did nothing to reduce brake fade, which was a problem for these very heavy cars. The Sure-Track system became standard equipment on the Mark III in 1970"	(Severson, 2009)
1960s-70s	"The potential relevance of ABS systems to the safety of the roads was discovered during the 1960s and early 1970s. A number of studies demonstrated that 10% of all the accidents with heavy vehicles and 8% of accidents with cars were due to slipping [24], and that a large fraction of these accidents could be avoided if systems to prevent wheel lock were used. As a result, initial tests to install ABS systems in trucks started in the early 1970s. Nevertheless, the initial solutions proved to have poor reliability and a prohibitively high price."	(Veloso and Fixson, 2001, p. 248)
1970	[electronic ABS] "This was first created by Bosch and they had it ready for 1970. Ready, but not reliable, it took them no less than 8 years to get it right, and it was then proposed as an option on the Mercedes S Class, and a year later on the BMW 7 Series. Since then it gained more functions, and more importantly maybe a sturdier build and lots of weight, but in the good direction: while ABS 2 (the first production ones) weighed 6.3 kgs and had 140 components in the control unit, the newest one (ABS 8.0), unleashed in 2001, weighs only 1.6 kg with 10 components in the control unit, and all this by achieving much, much more, quicker, better."	https://forums.finalgear.com/questions-and-answers/abs-from-dunlop-maxaret-to-a-1-6-kg-blackbox-1732/
1970	"[…] Daimler-Benz introduced this first generation of an anti-lock braking system for cars, trucks and buses to the public on the test track in Untertürkheim on December 12, 1970 – with a resounding echo by an enthusiastic expert world and press. The principle had been found to be convincing."	(Daimler Communications, 2008)
1970	In 1970, Teldix, in collaboration with Daimler-Benz, presented the first trial vehicles equipped with the system christened "ABS 1". Series introduction was to follow as soon as "possible, but the reliability of the control electronics still left much to be desired. In the case of a system acting on the operation of the brakes, it was necessary to fulfil maximum safety requirements, and this was still way off. With a control unit which at that time still had over 1,000 components, the number of potential sources of error was still decidedly too high."	(Robert Bosch GmbH, 2003a, p. 32)
1970	"A new Sure-Track Brake System is standard on Mark III [note: referring to 1970 Lincoln Continental Mark III]. It is the most advanced automotive braking system in the world – the safer, straighter way to stop a car. This computer-controlled system improves braking stability by preventing sustained rear wheel lock-up on ice, snow or wet pavements. When the driver slams his brakes in a panic stop, Sure-Track's electronic monitors take over, automatically actuating and releasing brakes until the car slows to 4mph, or until the brakes are released […]"	http://www.oldcarbrochures.com/static/NA/Lincoln/1970_Lincoln/1970%20Lincoln%20Continental%20Brochure/1970%20Lincoln%20Continental-15.html
1970	"General Motor's Cadillac division employed a simplified version of anti-lock brakes called Track Master. This system worked solely on the rear brakes and was introduced in 1970 on the Eldorado coupe and made an option for the entire line in the following year."	http://www.motorcars.in/brakes/abs.htm
1970-71	"I HAD come [in November 1970] to Detroit to test the '71 automobiles […] Chrysler […] The Imperial offers Sure Brake – a good automatic anti-skid brake	(Behme, 1970, p. 113)

	system."	
1971	"ABS would not start to enter the mainstream until Chrysler introduced the 1971 Imperial. Some other American manufacturers, notably Lincoln and General Motors, had previously added rear-wheel only ABS to their cars, but it was the Imperial that first gave the world reliable four-wheel anti-skid technology. Japanese manufacturers followed shortly with the Nissan President sported ABS on its comprehensive options list."	(Lawes, 2014)
1971	"Although the antilock braking concept is at least 20 years old, its adoption for cars has been slow, despite the pioneering efforts of Ferguson Research. Apart from Jensen's FF model is found only on a few of the more expensive Chryslers and (mostly for rear wheels only) on the more recent and prestigious versions of certain Ford, Lincoln, and Cadillac models – a handful of cars altogether compared with the total produced annually in America and Europe."	(Curtis, 1971, p. 359)
1971	"Japan's first ABS (EAL=Electro Antilock System) installed as an option to the first generation Nissan President. […] The electromagnetic sensor set on the front end of final drive detected the number of revolutions of the rear wheels. The EL control module analyzed signals from the sensor, and an actuator (the operative mechanism) automatically controlled the strength and operation of fluid pressure. […] Option on some models. […] Year manufactured: 1971 Manufacturer: Kelsey Hayes Corporation […] Model Name : Installed in Nissan President H150"	https://www.jsae.or.jp/autotech/data_e/5-4e.html
1971	"Testing a '71 model [note: 1971 Imperial LeBaron with Bendix 4-Wheel Anti-Skid Brakes] […] our interest is not so much the Imperial but its four-wheel "Sure-Brake" system. This Bendix device is obviously 100% more sophisticated than the Kelsey-Hayes two-wheel arrangement offered for several years on some Ford nameplates […] Surprisingly, this relatively low-priced ($351) option hasn't done much if anything to spark '71 Imperial sales. Perhaps this is because not enough people have heard about it, coupled to the fact that even fewer buyers in this price class (who opt for American machinery) can be termed "knowledgeable enthusiasts". Sure-Brake is being continued for '72 […] Bendix, on the other hand, may even be looking forward to the advent of ABS, an essentially similar system that will become available on larger Mercedes. Mercedes owners are the type who will spread the gospel. In the meantime, Bendix is plugging applications for highway trucks where the advantages are very real. Here, as much as $9,000 worth of tires are at stake as well as freedom from the ever-present danger of jackknifing a trailer rig. It would also seem to have application to four-wheel drive vehicles where a skid on a narrow trail couple topple you off on a mountainside."	(Road Test, 1971)
1972	"[1972 Cadillac Brochure] TRACK MASTER This computerized, rear wheel, skid-control braking system is now available on all Cadillac models."	http://www.oldcarbrochures.com/static/NA/Cadillac/1972_Cadillac/1972_Cadillac_Brochure_1/1972%20Cadillac-25.html
1972	"The Cadillac Eldorado […] rear-wheel antilock brakes." "The Chrysler Imperial […] its Sure-Brake four-wheel anti-lock system […]"	Popular Science, May 1972 http://imperialclub.com/Articles/72PopularScience/
early 1970s	"In the early '70s, Bendix introduced a four-wheel electronic ABS on the Chrysler Imperial (only 4,000 were sold)"	http://www.findarticles.com/p/articles/mi_m0BQA/is_1_81/ai_82551551/pg_2
1973	"If measured by sales, Sure-Brake was a failure, probably going on less than 5 percent of Imperials through 1973, so just a few hundred cars per year, at most. It did not return for 1974."	(Koscs, 2013)

1973	"After acquiring a 50 percent holding in Teldix in 1973, Bosch became involved in the project. Developers at Bosch had also been working on an electronically controlled antilock system, and the company had a wealth of experience in the area of automotive electronics – as a result of developing the Jetronic electronic gasoline injection system, for example."	(Kuhlgatz, 2014, pp. 55–56)
1975	"Pooling of ABS activities at Bosch"	(Kuhlgatz, 2014, p. 54)
1975-76	"The Sure-Track system became standard equipment on the Mark III in 1970, and it was also standard on the later Continental Mark IV through 1975. It reverted to option status in 1976, but it remained available on the Mark series until the downsized Fox-platform Continental Mark VI of 1980. It was also offered for several years on the Continental."	(Severson, 2009)
1975-78	"In 1975, the two Teldix partners Bosch and AEG, decided to make the development of ABS the sole responsibility of Bosch, which had been working on anti-braking system since 1969. The aim was ABS 2, a system ready for series production for which the know-how of Bosch and Teldix was bundled. Bosch provided experience with digital electronic components which were low-priced, efficient and sturdy enough for use in series-manufactured vehicles. ABS was presented in November 1978."	(Robert Bosch GmbH, 2003a, p. 32)
1975-78	"In 1975, Bosch took over full responsibility for ABS development. It bought up the remaining Teldix shares in 1981. The main contribution made by Bosch was its development and manufacturing experience with electronic components, which had reached a stage where they were robust enough for use in vehicles. For example, Bosch had long been using them in regulators for alternators and in injection systems. These components significantly improved the computing performance of the ABS central control unit, dramatically reduced the number of components in the control unit itself by employing highly integrated circuits, and at last ensured the level of reliability that was needed. The result, in 1978, was known as 'ABS 2'."	(Kuhlgatz, 2014, p. 56)
1975	"In Arjeplog, northern Sweden, Bosch tests chassis systems on frozen lakes. The picture shows an Audi 100 GL featuring a pilot version of ABS (1975)."	(Kuhlgatz, 2014, p. 53)
1975	"ABV antilock system for trucks presented by Knorr and Bosch."	(Kuhlgatz, 2014, p. 55)
1978	"The German firm Bosch had been developing anti-lock braking technology since the 1930s, but the first production cars using Bosch's electronic system became available in 1978. They first appeared in trucks and the Mercedes-Benz S-Class. BMW started using ABS at the time, making the technology standard on all vehicles in 1986. ABS Systems were later introduced on motorcycles." "Modern brake control systems were introduced for luxury-class cars. The first models to have ABS were the Mercedes-Benz S-Class and the BMW 7 Series."	http://www.motorcars.in/brakes/abs.htm (Kuhlgatz, 2014, p. 57)
1978	"Another eight years passed [i.e. 1978] before Daimler-Benz was able to offer a reliably functioning anti-lock braking system for production cars; this time was required to give the prototype the degree of technical maturity and reliability that is indispensable for large-scale production. In development, the engineers benefited from the revolution in electronics. It was not until the invention of integrated circuits that small, robust computers could be built, capable of recording wheel sensor data in next to no time and reliably actuating the valves for adjusting brake pressure. It took development partner Bosch five years to supply the first digital control unit to Untertürkheim for test purposes. Digital instead of analogue: this meant fewer components with the advantage of the risk of malfunction being reduced down to virtually zero. Thanks to digital technology, the electronic components were capable of recording, comparing, evaluating and transforming sensor data into governor pulses for the brakes' solenoid valves within milliseconds. What's more, not only the front wheels but also the rear wheels were included in the control operations."	(Daimler Communications, 2008)

1978	“Thus, it had taken a long, long time before Mercedes-Benz became the world's first motor manufacturer in August 1978 to officially launch the second-generation anti-lock braking system and to offer it as an option from December 1978 – initially in the S-Class at a surcharge of DM 2,217.60.”	(Daimler Communications, 2008)
1978	“The picture from 1978 shows the Mercedes-Benz S-Class W 116, the first to be equipped with the Bosch ABS.”	(Kuhlgatz, 2014, p. 53)
1978	“Start of production-line installation of the first antilock braking system ABS 2 in Mercedes-Benz and then BMW vehicles.”	(Robert Bosch GmbH, 2003b)
1978	“Bosch ABS 2 antilock braking system.”	(Kuhlgatz, 2014, p. 55)
1978	“In 1978 Bosch was the world’s first automotive supplier to present an ABS system ready for mass production. By October that year, the ABS 2 was available on the market for the first time in S-Class cars from Mercedes-Benz. Integration in the BMW 7 series followed in December.”	(Robert Bosch GmbH, 2003b)
1978	“However, it was the German firms Bosch and Mercedes-Benz that achieved a major automotive milestone with the launch of the first completely electronic four-wheel multi-channel ABS system in the Mercedes-Benz S-Class in 1978. They had been co-developing anti-lock braking technology since the 1930s.”	http://www.roadsafe.com/magazine/2008spring/abs.htm
1978	“The first electronic antilock braking system was a Bosch system fitted to a Mercedes production car in 1978, and with this the term ‘ABS’ (which comes from the German term ‘Anti Blockier System’) came into general use to mean an antilock braking system.”	(Day, 2014, p. 386)
1978	“[I]t was not until the advent of electronic control systems and electromagnetically sensed wheel speeds, beginning with the introduction of the Anti Blockier System (ABS) in 1978 by Robert Bosch working in conjunction with Mercedes-Benz, that the development of anti-lock braking systems started in earnest and has led to their increasing adoption.”	(Nunney, 1992, p. 572)
1978	“By the mid-seventies, however, Bosch and Teves developed similar electronic systems, which began to appear on high-end European cars in 1978. Lincoln was the first American manufacturer to reintroduce anti-lock brakes, introducing Teves ABS on the Continental Mark VII in 1984.”	(Severson, 2009)
1980	“Bosch sells 24,000 Antilock Braking Systems.”	http://www.bosch.de/start/media/BOSCH_ABS_Infowand_eng.pdf
1980s	“Since the components of the system had been cut to 140, its micro-electronics now displayed the reliability needed in cars. In the following years, the main aim was to make the system smaller, lighter and more effective.”	(Robert Bosch GmbH, 2003b)
1981	“Delivery of the 100,000th ABS; ABS now also fitted in trucks.”	(Robert Bosch GmbH, 2003b)
1981	“After acquiring a 50 percent holding in Teldix in 1973, Bosch became involved in the project. […] It bought up the remaining Teldix shares in 1981.”	(Kuhlgatz, 2014, pp. 55–56)
early 1980s	“Antilocks were first used on airplanes beginning in the 1950s and have been used extensively on large trucks in European countries since the early 1980s.”	http://www.angelfire.com/journal2/carcareguide/habs.html
1982	“A comparable system was introduced for commercial vehicles in 1982, based on the standard pneumatic brakes used in this segment.”	(Kuhlgatz, 2014, p. 56)
1983	“Bosch ABS 2S was developed. The weight of the 2S hydraulic unit is reduced from 5.5 kg to 4.3 kg. This system employs a new integrated circuit which further improves the structure of the ABS logic. The integration of components in the electronic control unit halves the number involved, by comparison with ABS 2, to 70. 0.3% installation rate of ABS”	http://www.bosch.de/start/media/BOSCH_ABS_Infowand_eng.pdf
1984	“As a result, initial tests to install ABS systems in trucks started in the early 1970s.	(Veloso and Fixson, 2001, p.

	Nevertheless, the initial solutions proved to have poor reliability and a prohibitively high price. Therefore, it was only in 1984 that Bosch and ITT-Teves introduced the first [note: not first] commercial car ABS system, already based in microprocessor technologies."	248)
1984	"Since 1984, ABS has been standard equipment on Mercedes-Benz passenger cars."	(Daimler Communications, 2008)
1984	"In 1984, Bosch founded the joint venture Nippon ABS with a Japanese partner. That very same year, the Mitsubishi Galant and the Nissan Fairlady were available with ABS."	(Kuhlgatz, 2014, p. 55)
mid 1980s	"In Europe ABS became standard specification on heavy commercial vehicles and coaches in the mid 1980s, and this was followed by a mandatory requirement in 1991."	(Day, 2014, pp. 386–387)
1985	"Ford finally brought ABS to the European mainstream with its Scorpio in 1985. Made in Cologne, it was effectively a stretched Sierra with a few more luxuries, but it was almost certainly the standard fitment ABS that contributed to it winning the Car of the Year in 1986, at a time when motoring press was becoming more interested in the safety of the vehicle's occupants."	(Lawes, 2014)
1985	"BMW now offers ABS as standard in all models in the 600 and 700 series and in the M535i. Bosch and Nippon Air Brake Ltd. Found the joint venture "Nippon ABS" in Japan. From here, Japanese customers are supplied with ABS."	http://www.bosch.de/start/media/BOSCH_ABS_Infowand_eng.pdf
1985	"First ABS systems from Bosch are installed in US vehicles." "Bosch ABS in U.S. vehicles for the first time."	(Robert Bosch GmbH, 2003b) (Kuhlgatz, 2014, p. 55)
1985	"The first car to have ABS fitted as standard was the Ford Granada Mk 3 [note: except for the UK and Ireland, it was known as Scorpio] (of 1985)." [note: there were models with standard ABS from the 1970s-80s]	http://www.motorcars.in/brakes/abs.htm
1986	"One million Bosch ABS delivered."	(Robert Bosch GmbH, 2003b)
1986	"The millionth ABS system was supplied in 1986."	(Robert Bosch GmbH, 2003a, p. 33)
1986	"By 1986, the first million systems [i.e. ABS units] had been delivered."	(Kuhlgatz, 2014, p. 56)
1986	"ABS3: ABS and brake booster in one component"	(Kuhlgatz, 2014, p. 55)
1986-87	"On the basis of ABS, Bosch brought the first traction control system (TCS) for motor cars to mass production in 1986. It prevents wheel slip, permitting cars to accelerate better on slippery ground with improved traction (accelerative force) and driving safety. When bends are driven too fast, the system also improves driving stability by reducing drive torque. [1987] Start of mass production of the TCS traction control system for passenger cars."	(Robert Bosch GmbH, 2003b)
1986	"Eight years after the ABS was introduced in 1978, Bosch launched TCS (or traction control), which had been the subject of intense research since 1980. Just as ABS stops brakes from locking during braking, TCS prevents wheels from spinning during start-up and acceleration."	(Kuhlgatz, 2014, p. 56)
1986-87	"The success of Bosch and ITTTeves rushed other competitors to the market and, over the following years, a number of other ABS products became available. Lucas signed contracts to supply Ford in 1986. In Japan, Nippondenso and Sumitomo started production in 1986 and 1987. In the next years, many others were to follow."	(Veloso and Fixson, 2001, p. 249)
1987	"Front- and rear-wheel antilocks were available as standard or optional equipment on about 30 domestic and foreign car models by the 1987 model year."	http://www.angelfire.com/journal2/carcareguide/habs.html
1987	"Since a traction control system may be regarded as a logical but inverse development of anti-lock brakes and can therefore utilize some of the same technology, it is perhaps to be expected that this type of system was pioneered by	(Nunney, 1992, p. 579)

	Robert Bosch working in conjunction with Mercedes-Benz, their anti-slip control system being introduced in 1987 and known as Antriebs-Schlupf-Regelung (ASR)."	
1987	"Kelsey Hayes launches two wheel ABS system" [researcher's note: most likely referring to ABS for motorcycles]	http://www.britishcarcouncil.com/history/lucas.html
1988	"Ten years after the introduction, as many as one million Mercedes-Benz cars with ABS were being operated on the roads throughout the world."	(Daimler Communications, 2008)
1988	"The first antilock braking system for motorcycles came onto the market in 1988, ten years after ABS was introduced for passenger vehicles."	(Robert Bosch GmbH, 2015)
1988	"Bosch has supplied over 3 million ABS units since the introduction of series production."	http://www.bosch.de/start/content/language2/html/734_2880.htm
1991	"About 18% of new cars sold in the 1991 model year had antilocks, 32% in the 1992 model year had them, and manufacturers' projections indicate the percentage will continue to grow. (Ward's Automotive Reports 1989-1991)"	http://www.angelfire.com/journal2/carcareguide/habs.html based on (Ward's Automotive Reports 1989-1991)
1992	"[1992] 10 million ABS from Bosch." "[1992] Ten million ABS"	(Robert Bosch GmbH, 2003b) (Kuhlgatz, 2014, p. 56)
1992	"ABS becomes standard equipment in all Mercedes-Benz models."	http://www.bosch.de/start/media/BOSCH_ABS_Infowand_eng.pdf
1993	"In 1993 Bosch developers built the generation 5.0 with new magnetic valves. It was followed by the 5.3 and 5.7 versions. Additional functions were added, e.g. electronic brake force metering which replaced the mechanical brake force proportioning valve on the rear axle."	(Robert Bosch GmbH, 2003b)
1994	"[sub-title: Antilock braking system has been made in Japan since 1994] Bosch started to develop motorcycle ABS at the end of the 1980s, basing it on the system designed for passenger cars. The first systems finally rolled off the production line in 1994. They were installed in Suzuki police bikes in Japan. In the following years, volumes grew only slowly."	(Robert Bosch GmbH, 2013)
1994	"Bosch also supplied an ABS for motorcycles from 1994."	(Kuhlgatz, 2014, p. 56)
1995	"[1995] ABS 5.3 from Bosch starts mass production (with connected control device in micro-hybrid construction); serial manufacturing of the Electronic Stability Program (ESP®) starts. […] The Electronic Stability Program (ESP®) was first brought to market by Bosch in 1995. It improves vehicle stability not only in braking and accelerating, but in all driving situations, and incorporates ABS and TCS. If a car threatens to skid, ESP® cuts engine performance and brakes individual wheels, thereby improving driving safety considerably"	(Robert Bosch GmbH, 2003b)
1995	"[referring to motorcycles] In 1995, Bosch started series production of the first antilock braking system. The ABS generation 2L1 had a considerable weight of 4.5 kg. At that time, all motorcycle ABS systems were based on the model from the automobile industry. However, the braking characteristics for a two-wheeled vehicle are completely different to those of a four-wheeled vehicle. For this reason, our engineers developed the first ABS system specially designed for motorcycles with the generation 9 [note: launched in 2009]. The system is modular in design, allowing it to be adapted to a wide range of models: from light motorcycles to heavy-duty tourers."	(Robert Bosch GmbH, 2015)
1999	"[1999] 50 million ABS from Bosch."	(Robert Bosch GmbH, 2003b)

	“[1999] 50 million ABS”	(Kuhlgatz, 2014, p. 56)
2000	“60 percent of all new cars worldwide are equipped with ABS.”	(Robert Bosch GmbH, 2003b)
2001	“The current ABS generation is the ABS 8 introduced by Bosch in 2001. This is a modular system which permits the ABS, TCS and ESP® braking control systems to be implemented as an integrated product family. This has resulted in optimal use of synergies in production and development. These technological advances have led to higher performance, less components and lower weight of the ABS. Whereas the ABS 2 (1978) weighed 6.3 kg, the ABS 8.0 of 2003 weighs a mere 1.6 kg.”	(Robert Bosch GmbH, 2003b)
2003	“Since production-line manufacturing of ABS took off in 1978, Bosch has delivered 100 million ABS systems worldwide.” “[2003] 100 million ABS”	(Robert Bosch GmbH, 2003b) (Kuhlgatz, 2014, p. 57)
2004	[reflecting views about the future] “Soon, no new car in Europe is to come without an antilock braking system. The European federation of automotive manufacturers has committed itself to fitting all news cars sold in Europe with ABS as standard from mid-2004 onwards.”	(Robert Bosch GmbH, 2003b)
2004	S”ince July 2004, every new car sold in Europe has had an antilock braking system as standard equipment.”	(Kuhlgatz, 2014, p. 57)
2007	“[…] ABS as standard, even on the most basic models, as it has been mandatory in new cars sold in Europe since 2007.”	(Lawes, 2014)
2009	[referring to motorcycles] “In 2009, the company [i.e. Bosch] launched the first ever system designed specifically for motorcycles. This was followed in 2010 by the world’s smallest system for motorcycles.”	(Kuhlgatz, 2014, p. 56)
2009	[referring to motorcycles] “This changed in 2009. First of all, interest in safety technology picked up and, second, Bosch launched its new flagship Generation 9. For the first time, this was a solution that was not derived from passenger-car technology, but instead developed specifically for use in motorcycles. The result was high performance at half the size and weight of the predecessor generation. Demand exceeded all expectations. As a result, production has risen by an annual average of more than 50 percent since 2009.”	(Robert Bosch GmbH, 2013)
2013	[referring to motorcycles] “In Tochigi, Japan, the one-millionth Bosch safety system has now come off the production line.”	(Robert Bosch GmbH, 2013)
2013	[referring to motorcycles] “In 2013 alone, roughly 350,000 systems have been manufactured. Now, every fourth motorcycle made in Europe has ABS on board.”	(Robert Bosch GmbH, 2013)
2013	[referring to motorcycles] “Worldwide ABS installation rate 1%”	http://www.bosch-motorcycle.com/media/ubk_zweiraeder/related_content/downloads/Installation_rates_worldwide_2013.jpg

3.5. Market actors and factors

Year(s)	Market actors and factors innovation phase	Description of their influence or role	Source
1939-1945	world war	“Many technological advances were accelerated by the outbreak of the Second World War, but the production of ABS […] was largely marginalized.”	(Lawes, 2014)
prior to 1950s	knowledge of the physical principles	“While antiskid devices have been dreamed about for years […] there was little or no practical progress because they [i.e. engineers] couldn’t agree whether skidding was a help or a hindrance in stopping a car. Many	(Cutter, 1968, p. 105)

		engineers insisted that the greatest amount of deceleration occurred during tire skidding. Then, about 10 years ago [i.e. late 1950s], a group of British engineers arrived at the fairly definite conclusion that maximum retardation could be achieved with a 15 percent skid."	
Year(s)	Market actors and factors market adaptation phase	Description of their influence or role	Source
late 1940s – 1952	Dunlop, Britain's Ministry of Supply and US firms Hydro Aire and Westinghouse	"Wheel-lock can be difficult or impossible to detect from the cockpit, and causes very rapid tyre wear and loss of braking effectiveness due to the reduction in friction. Several devices to prevent wheel-lock made their appearance, for example from the US firms Hydro Aire and Westinghouse. Britain's Ministry of Supply wanted urgently to investigate anti-skid techniques and pressed Dunlop to take out a patent to licence-build an American unit. The Coventry firm [i.e. Dunlop] was not keen to do this, and Trevaskis [company's technical director at the time] evolved an ingenious device to prevent wheel slip, relying on the inertia of a small heavy disc rolling in contact with the inside of the wheel rim to cut off the hydraulic pressure when relative motion between the disc and the rim indicated the onset of lock. Entirely mechanical and automatic in operation, it had a diameter of about 5in, weighed just a couple of pounds and was tested on a Devon. As a "fit and forget" item it has enjoyed a deserved popularity under the trade-name Maxaret. […] Like every other Dunlop aeronautical venture[,] the Maxaret was developed with private money. The company has always been opposed to seeking Government assistance and down to the present day [i.e. 1975] has managed to keep this independent outlook, though with the high investment now demanded by R&D, for example in carbon brakes, this attitude is becoming harder to maintain."	(Ramsden et al., 1975, pp. 607–608)
1958	knowledge of the technology	"So it was as a result of the experience gained in this field that the possibility of adapting the Maxaret system for use on motor vehicles was investigated by the Dunlop company and an installation tested by the Road Research Laboratory. At this juncture it must be appreciated that the objectives sought in applying the wheel anti-lock principle to aircraft and motor vehicle braking systems were somewhat different. With an aircraft the objectives are to prevent at least expensive tyre damage and at worst a potentially dangerous tyre burst, by avoiding wheel locking however briefly it may occur during […] In comparison with an aircraft tyre, the tyre of a motor vehicle is relatively lightly loaded and any damage caused to it by wheel locking is far less significant, but what is really important is any loss of directional control or stability as already mentioned."	(Nunney, 1992, p. 572)
1960s – 1970s	product need by customer segments	"Early thinking on anti-lock brake systems for motor vehicles was therefore directed not only towards passenger car applications, but also for commercial vehicles with the jack-knifing problem on articulated ones especially in mind."	(Nunney, 1992, p. 572)
n.d.	ABS technical requirements of car versus aircraft or railway systems	"But in the car, the demands on the mechanical friction wheel sensors were much higher: they had to register decelerations and accelerations in wheel speeds, they had to react reliably in corners and on rough ground and work perfectly even when heavily soiled and at high temperatures."	(Daimler Communications, 2008)
1965	Jensen & Dunlop	"Antiskid next bobbed into public view in 1965 on the expensive British Jensen FF equipped with a Dunlop Maxaret unit converted from an aircraft system."	(Cutter, 1968, p. 206)

1966	critics of the technology	"Early critics of the FF [i.e. Ferguson Formula] (many with axes to grind) tried to suggest that, while giving an improvement in the wet, it actually increased the stopping distance a little in the dry. When this proved to be essentially unfounded, they said that the system lacked sufficient rapidity of response to cope with a wide variety of surfaces and conditions – even though it was known to operate at up to nearly seven cycles per second."	(Curtis, 1971, p. 359)
since 1966	speed of response drove the shift from mechanical to electronic systems	"[T]hey [i.e. critics] said that the system lacked sufficient rapidity of response to cope with a wide variety of surfaces and conditions – even though it was known to operate at up to nearly seven cycles per second. Though no impartial comparative tests have been publicly conducted, there may have been some substance in this criticism; at any rate it speeded the realisation that antilock brakes must be electronically controlled if significantly improved responses were to be achieved. […] For these reasons, all the numerous experimental systems announced since the Jensen FF came on the market have been electronic in operation."	(Curtis, 1971, p. 359)
1966	new high-tech product; knowledge of the technology	"Another fundamental problem was to find a way of relieving and restoring the pressure in a conventional hydrostatic braking system without the recourse to the alternative of fully powered braking – though some experimental systems working with fully powered brakes have been announced (by Lockheed among others). As already mentioned, Ferguson solved this problem with their ingenious double-sided vacuum servo […] It can also be solved by bleeding some hydraulic fluid from the system and then restoring it with a small electrically driven pump. This is in fact the method developed for Mercedes-Benz by Teldix […]"	(Curtis, 1971, p. 359)
early 1960s	semiconductor technology, i.e. electronic systems	"It was only the introduction of the semiconductor technology, available from the early 1960's, that created the preconditions for the necessary rapid triggering of the [ABS] system."	(Robert Bosch GmbH, 2003a, p. 31)
n.d.	electronic and hydraulic systems; product need by segment (trucks)	"As the electronic and hydraulic portions of aircraft ABS became smaller and less expensive, truck and automobile manufacturers began to take interest. At first, antilock brake systems were developed only for heavy-duty trucks. Large semi trucks—truck tractor-trailer combinations weighing up to 80,000 pounds (36,364 kg)—were especially hazardous to traffic around them when they skidded since they not only moved out of the driver's control, but also articulated, or jack-knifed, and frequently rolled over. Today, antilock brake systems are standard on many cars and trucks."	(Joel, 1996)
1966; 1978	electronics control systems and electromagnetic wheel speed sensors	"Although the Dunlop Maxaret anti-lock principle was eventually adapted to the braking system of the specialist Jensen FF four-wheel-drive car in 1966, it was not until the advent of electronic control systems and electromagnetically sensed wheel speeds, beginning with the introduction of the Anti Blockier System (ABS) in 1978 by Robert Bosch working in conjunction with Mercedes-Benz, that the development of anti-lock braking systems started in earnest and has led to their increasing adoption."	(Nunney, 1992, p. 572)
1964	high investment costs; availability of integrated circuits	"Fundamental research work on the problem [i.e. electronically controlled ABS systems] had begun here [i.e. at Teldix GmbH] as early as 1964. It was realized that while electronically controlled anti-blocking systems were feasible, their development involved such immense financial investment that their use was virtually limited to aircraft and express trains. The cost of the basic electronics needed for an efficient system, however, had to be tailored to the equipment's use in series-	(Robert Bosch GmbH, 2003a, pp. 31–32)

		production vehicles, and it was thanks to the availability of integrated circuits from the 1964 on. Only two years later, prototypes were already able to cut braking distances."	
since 1970s	emphasis on automobile safety	"Since the 1970s, the addition of computer-controlled sensors and a general emphasis on automobile safety has led to a rapid evolution of the effectiveness and popularity of ABS."	http://www.europeanbrakingsystems.co.uk/history
1966	Jenson FF: performance, cost, right-hand drive, production	"That was a bit of a stretch, considering that the mechanical Dunlop Maxaret ABS system (developed for airplanes) only pulsed the brakes three times a second compared to 20 times per second in modern systems. […] The world's first AWD road car did have one major design flaw. It only came as a right-hand driver. […] Tragically, America was Jensen's biggest market. Couple that with the as-much-as-a-house price (more than one house in some cases) and demand wasn't exactly heavy. Out of the 320 FFs built, only one was sold in the States." "The disadvantages of the Maxaret system are likely to be its cost and complexity (except when used on certain types of car, such as the Ferguson [researcher's note: the text also mention that the Maxaret system on the Ferguson was much simpler, as it required only one Maxaret unit to operate all four wheels]). The cost aspect is perhaps not so important for the larger commercial vehicles but efforts are now being made in this country and abroad to develop simpler devices based on the principles already mentioned."	http://jalopnik.com/267959/jensen-ff (Starks, 1968, p. 10)
early 1970s	reliability & costs in trucks	"As a result, initial tests to install ABS systems in trucks started in the early 1970s. Nevertheless, the initial solutions proved to have poor reliability and a prohibitively high price."	(Veloso and Fixson, 2001, p. 248)
1966	Chrysler	"Chrysler fitted their new four-wheel "Sure Brake" ABS system into some of their 1966 models but it "did not perform up to expectations". [researcher's note: year and experiment not corroborated with other sources] Chrysler entered into a joint venture with Bendix and developed a computerized, three-channel, four-sensor all-wheel ABS version of "Sure Brake"."	http://www.carhistory4u.com/the-last-100-years/parts-of-the-car/brakes
1968	Kelsey-Hayes Co.	"Kelsey-Hayes Co., an auto supplier headquartered in Romulus, Mich., has taken a proven aircraft antiskid system and has rather quickly converted it into a relatively simple – but still electronic – automobile unit. Kelsey-Hayes has built more than 100 prototypes that are now being tested by automakers. And, importantly, the engineers already have data on this technically tricky mechanism based on more than 10,000 instrumented stops. […] Kelsey's system is fundamentally a rear-wheel unit. Kelsey's engineers feel it's most important to move into this field slowly with a simple, low-priced system that will prevent rear-end slewing."	(Cutter, 1968, p. 206)
1968	Bendix Corp.	"Among those disputing the 15 percent slip theory are the Bendix engineers who have developed a so-called "adaptive antiskid system". This is a more sophisticated electronic unit which stops the car with very rapid and slight "snubs" that are applied in the fraction of a second before lockup occurs, rather than waiting for the actual skid. […] Bendix is also working overtime on a very exotic "full-power" antiskid in which hydraulic force, instead of vacuum, power the antiskid unit as well as the regular brakes." (p. 105) "By contrast Bendix thinks that the front-end antiskid should be included in the system because it would provide the all-important	(Cutter, 1968, pp. 105, 206)

		steerability and because most of the braking in a panic stop is done by the front brakes." (p. 206)	
1969	Dunlop	"By using electronic skid-sensing, the Dunlop Co. Ltd., Coventry, says it has both improved the performance and lowered the cost of its Maxaret anti-skid system for air-braked commercial vehicles. But it will not be generally available until late in 1969. A number of operators' vehicles are being equipped with pre-production sets of the latest Maxaret, and full-scale production will not start until the results of these operational trials have been declared satisfactory. […] In its latest form the Maxaret is expected to cost only about £60 to operators. The previous model cost £120."	http://commercial-motor.archive.netcopy.co.uk/article/27th-september-1968/52/cheaper-and-better-maxaret
(1964-)1970	Teldix	"This is, in fact, the method used in the electronic system developed for Mercedes-Benz by Teldix, a consortium of the West German Telefunken and the American Bendix companies (Ducellier-Bendix group is also interested in antilock brakes). In a demonstration last December [i.e. 1970], Mercedes cars fitted with this system […]"	(Curtis, 1971, p. 359)
1968	geographical preferences regarding technological complexity	"The ultimate antiskid is a four-wheel system, perhaps something like the British Maxaret unit. But there's strong belief at the U.S. auto companies that the first step should a low-cost, simple unit."	(Cutter, 1968, p. 206)
1971	geographical preferences by suppliers	"If antilock brakes are to be introduced, Ingram [note: Brian Ingram, chief engineer of Special Control Projects, at Girling, UK] would prefer them to be fitted to the rear wheels only at first – as it is happening now in the United States. These systems go one stage further than the load-sensitive pressure-relief valve in minimizing yaw, but are not highly regarded by the majority of the European observers because they give little to no reduction in stopping distance and cannot prevent the ability to steer from being lost when the front wheels lock-up."	(Curtis, 1971, p. 360)
since 1970s	modularity; advantage to scale for suppliers over vehicle manufactures	"As a result, there have been greater incentives for the suppliers to be responsible for the product, because they could split the investment across different assembler clients. […]The solution just described is clearly independent from the vehicle where it is applied. Therefore, if we consider the incentive structure associated to the development of the innovation, and frame it in the scenarios described in the previous sections, we clearly understand that the suppliers are facing much larger economic incentives that the assemblers to promote the development of such an innovation. If the supplier succeeds, his potential market includes all the automakers (OEMs). If the assembler succeeds, then his potential market is likely to be only their cars, as he probably would not be willing to pass the innovation to another automaker. Our perception is that, since the 1970s, suppliers were aware of the market opportunity for the introduction of the ABS, provided that they were able to meet the necessary reliability and safety concerns of the automaker. Therefore, it is not surprising to find Bosch and ITT-Teves leading the introduction of the ABS system. Nevertheless, this only means that these companies were successful in putting the ABS into the market."	(Veloso and Fixson, 2001, p. 250)
1960s – 1970s	road safety (trucks)	"The potential relevance of ABS systems to the safety of the roads was discovered during the 1960s and early 1970s. A number of studies demonstrated that 10% of all the accidents with heavy vehicles […] were due to slipping [24], and that a large fraction of these accidents could be avoided if systems to prevent wheel lock were used. As a result, initial	(Veloso and Fixson, 2001, p. 248)

		tests to install ABS systems in trucks started in the early 1970s. Nevertheless, the initial solutions proved to have poor reliability and a prohibitively high price."	
n.d.	Dunlop, D.B.A., Bendix, Automotive Products plc.	In fact, several firms with know-how about the product have been established for many years, including Dunlop, the original ABS innovator, D.B.A., Bendix, or Automotive Products plc.	(Veloso and Fixson, 2001, p. 249)
1968	Ford Motor Co.	"Shortly after the Jensen's introduction, Ford Motor Co. started a hard drive toward antiskid. During the past summer, Ford staged an informal antiskid competition asking all interested suppliers to demonstrate their hardware."	(Cutter, 1968, p. 206)
1968	Ford Motor Co., Kelsey-Hayes, Bendix, TRW (formerly Thompson-Ramo-Woolridge) and Eaton, Yale and Towne, Lockheed and Dunlop, Goodyear	"During the past summer, Ford staged an informal antiskid competition asking all interested suppliers to demonstrate their hardware. Among the auto supplier[s] demonstrating devices to Ford were Kelsey-Hayes, Bendix, TRW (formerly Thompson-Ramo-Woolridge) and Eaton, Yale and Towne, as well as two British brake suppliers Lockheed and Dunlop. Two Ford groups – Ford Research, and Ford Transmission and Chassis Division – have systems. Goodyear also has a system."	(Cutter, 1968, p. 206)
1968	price-performance, profit margin	"The improvement in braking is proportional to the complexity and cost of the unit. The cost of these systems [i.e. antiskid] will vary from $40 to $150 a car, but a real effort is being made to get the $40 system ready for all but the luxury cars. Because of their safety value, there appears to be an unspoken agreement among automakers to apply a minimum mark-up to antiskid devices."	(Cutter, 1968, p. 105)
late 1960s	Ford & Kelsey-Hayes	"In the late sixties, Ford Motor Company and brake manufacturer Kelsey-Hayes developed a more sophisticated system using magnetic wheel-speed sensors connected to an analog computer. If the sensors detected that the wheels were beginning to lock, the computer would automatically pump the brakes up to four times per second to prevent it. The system, called "Sure-Track," worked only on the rear wheels, which are the most vulnerable to lockup: As a vehicle decelerates, its weight shifts forward, which reduces the traction of the rear tires."	(Severson, 2009)
1968 – 1971	General Motors	"General Motors have publicly pooh-poohed antiskid. Yet some time ago GM car divisions pitched into antiskid research with a frenzy, concentrating on three different systems from General Motors Research, GM's Delco Morraine Div., and Eaton. Pontiac probably will offer antiskid in two years [i.e. 1970]. Buick and Oldsmobile have about the same objective, although maybe one year later [i.e. 1971]."	(Cutter, 1968, p. 206)
1970	price competition	"Yet, during the past year [i.e. 1970-71], a number of further experimental electronic systems have been announced by various companies – including Mullard, Bosch and Lucas – while the Teldix system is to become a Mercedes option later this year. All this suggests to the outsider that cheap antilock braking may be just around the corner."	(Curtis, 1971, p. 360)
1971	regulatory environment	[Note: as written in 1971] "The vehicle and brake manufacturers themselves, for example, say that antilock braking will not become widely adopted until nations build a requirement for them into their safety regulations."	(Curtis, 1971, p. 360)
1968	regulatory environment in US	"In addition to the secrecy that envelops any future automobile feature, there's considerable concern in Detroit that impatient Washington safety	(Cutter, 1968, pp. 105, 206)

		officials will force automakers to install antiskid systems before they're fully developed." (p. 105) "[…] Although some of the auto manufacturers are not so enthusiastic about antiskid, strong competition and government forces are now working to compel every maker to have antiskid braking in the next years. Extensive antiskid presentation already have been made by some of the developers for the U.S. General Services Administration and the National Highway Safety Bureau." (p. 206) "ABS was first required as a mandatory fitment in the USA in the 1970s, but this requirement was subsequently withdrawn as the technology was not robust at that time."	 (Day, 2014, p. 386)
1970s	regulatory environment in US versus Europe	"After a difficult start in the 1970s, when technology couldn't create an ABS that would meet the National Highway Traffic Safety Administration (NHTSA) standards, American trucking associations were able to halt implementation of the anti-lock brake requirements on new trucks. However, while Americans forgot about ABS, our European counterparts were working diligently to create an ABS that would improve truck safety for both tractors and trailers. Once the European Economic Council required ABS on all Class 8 trucks the NHTSA quickly followed suit."	http://www.philatron.com/hdinfo/absfaq.html
mid 1980s, 1991	regulatory environment Europe	"In Europe ABS became standard specification on heavy commercial vehicles and coaches in the mid 1980s, and this was followed by a mandatory requirement in 1991."	(Day, 2014, pp. 386–387)
1975	regulatory environment in Sweden (Europe)	[Note: forward looking statement; text written in 1971] "Just such a requirement [i.e. to fit ABS into their safety regulations], becoming effective 1975, is now on the statute books of Swedish government, who recently invited all interested brake and vehicle manufacturers to discuss the problems at a conference."	(Curtis, 1971, p. 360)
1971 – 1973	price variation	"The Mercedes system [i.e. Bosch] probably had an advantage with more modern digital controls, but the Imperial's Sure-Brake system, developed by Bendix, proved effective. The Sure-Brake option cost $351.50 on the 1971 Imperial, which started at just over $6,000. The option cost was reduced to $344 for '72 and '73. […] If measured by sales, Sure-Brake was a failure, probably going on less than 5 percent of Imperials through 1973, so just a few hundred cars per year, at most. […] Some might want to blame the option's price for the failure, but Sure-Brake cost less than a number of the Imperial's other extras, such as the AM/FM stereo with tape player." "Around the same time that Sure-Track was introduced, the Bendix Corporation developed an electronically controlled four-wheel system, which was offered on the Imperial from 1971 to 1973. Although it was more effective than Sure-Track, the Bendix system was more expensive (priced at $344) and was soon dropped due to lack of interest."	(Koscs, 2013) (Severson, 2009)
1971 - 1973	customers' knowledge of the technology	"As was often the case with new safety features [referring to the Imperial with Sure-Brake optional system], the manufacturer and its dealers probably failed to adequately market the technology and explain its benefits to customers."	(Koscs, 2013)
late 1970s – early 1980s	reducing technological complexity	[researcher's note: referring to the late 1970s, early 1980s] "Since the components of the system had been cut to 140, its micro-electronics now displayed the reliability needed in cars. In the following years, the main aim was to make the system smaller,	(Robert Bosch GmbH, 2003b)

		lighter and more effective."	
1980s	success stimulates similar product introductions on the market	"The success of Bosch and ITTTeves rushed other competitors to the market and, over the following years, a number of other ABS products became available. Lucas signed contracts to supply Ford in 1986. In Japan, Nippondenso and Sumitomo started production in 1986 and 1987. In the next years, many others were to follow. As Figure 3 illustrates, ABS was a clear market success, with demand for ABS growing rapidly."	(Veloso and Fixson, 2001, p. 249)
1968 - 1995	modularity; outside market; suppliers; intellectual property; market dominance	"Figure 4 shows patent activity throughout time from 1968 to 1995.11 As anticipated, the suppliers did most of the investment in the development of the ABS, which would indicate that they possess the ownership rights over the innovation. The assemblers did mainly complementary investments needed to incorporate the ABS in the car. […] Figure 5, […o]nce again, evidence appears to confirm that suppliers dominated the market. The existence of an outside market generated large incentives for independent suppliers, which led the development of the ABS from the early beginning, both in terms of ownership of the intellectual property, and market dominance. Moreover, we explained why the modular characteristics of both conventional and ABS braking systems played a crucial role in giving a clear up-front perception of the potential ABS market, and enabled development and testing somehow independent of the assembler."	(Veloso and Fixson, 2001, pp. 250–251)
n.d.	Daimler-Benz and cooperation partners Bosch, TELDIX and Wabco	"If the anti-lock braking system is today taken for granted in virtually all cars of the majority of automotive brands throughout the world, we owe this to the commitment of the large number of engineers and technicians at Daimler-Benz and cooperation partners Bosch, TELDIX and Wabco, who searched for the best solution for this system which improves handling safety, avoids accidents and saves lives."	(Daimler Communications, 2008)
n.d.	Delco & GM	"Figure 5, […a]s we can see, assemblers are only represented directly by Honda, and indirectly by Delco [note: development is being assured within a vertically integrated structure], a components firm owned by GM. Once again, evidence appears to confirm that suppliers dominated the market."	(Veloso and Fixson, 2001, p. 251)
Year(s)	Market actors and factors market stabilization phase	Description of their influence or role	Source
1985 – 2001 (forecasted until 2005)	increasing role and size of suppliers	"Several important changes have been happening in the automotive industry during the past decade. The most prominent one has been the rise of the supplier industry. From small players that manufactured individual parts, suppliers have grown to be partners of the assemblers, with design, testing, and manufacturing responsibilities, and an increasing global presence. An A. T. Kearney/University of Michigan study suggested that the transfer of direct task responsibilities began in 1985, and will continue through 2005, with as much as 80% of the value added of the car being bought from the suppliers rather than generated by the assembler."	(Veloso and Fixson, 2001, p. 239)
1988	regulatory efforts in Europe; unserved customer segment (light trucks in Europe)	"Although lighter trucks are a potential market for ABS, that market has not been served. Currently, the European approach is to concentrate on the heavier vehicles with GVW's over 9 tonnes. Legislative initiatives are directed at the heavier trucks and buses. According to ABS manufacturers and personnel at Daimler-Benz, there are almost no ABS systems on the lighter trucks in Europe."	http://deepblue.lib.umich.edu/bitstream/handle/2027.42/26/77201.0001.001.pdf

References (excl. direct links)

Barwell, F.T., 1973. Control of Braking, in: Automation and Control in Transport. Pergamon Press, Oxford, New York, Toronto, Sydney, Braunschweig, pp. 146–158. doi:http://dx.doi.org/10.1016/B978-0-08-016962-0.50019-7

Behme, B., 1970. Trailering with the New Cars. F. Stream 75, 112–115.

Commercial Motor, 1969. Electronic Maxaret in production. Commer. Mot. 42.

Commercial Motor, 1966a. Maxaret-Controlled Artic. Commer. Mot. 100.

Commercial Motor, 1966b. Shell's first Maxaret-equipped tanker demonstrated. Commer. Mot. 41.

Curtis, A., 1971. Taking the skid out of braking. New Sci. 51, 358–361.

Cutter, C., 1968. Coming Soon! "Skidproof" Cars. Pop. Mech. 129, 104–106, 206.

Daimler Communications, 2008. Mercedes-Benz and the invention of the anti-lock braking system: ABS, ready for production in 1978 [WWW Document]. URL http://media.daimler.com/dcmedia/0-921-657486-1-803841-1-0-0-0-0-1-11701-614318-0-1-0-0-0-0-0.html

Day, A., 2014. Electronic Braking Systems, in: Day, A. (Ed.), Braking of Road Vehicles. Butterworth-Heinemann, Oxford, pp. 385–428. doi:http://dx.doi.org/10.1016/B978-0-12-397314-6.00011-5

Hobbs, F.D., 1979. The Road User, the Vehicle and the Road, in: Traffic Planning and Engineering. Robert Maxwell, M.C., pp. 260–331. doi:http://dx.doi.org/10.1016/B978-0-08-022697-2.50013-8

Joel, S., 1996. Antilock Brake System [WWW Document]. How Prod. Are Made. URL http://www.encyclopedia.com/doc/1G2-2896600014.html (accessed 5.1.15).

Koscs, J., 2013. Anti-Lock Brakes: Who Was Really First? [WWW Document]. Hagerty. URL https://www.hagerty.com/articles-videos/Articles/2013/04/09/Antilock-Brakes

Kuhlgatz, D., 2014. Bosch Automotive: Supplement 2 of Bosch History Journal, Journal of Bosch History.

Lawes, J., 2014. Anti-lock Braking Systems, in: Car Brakes: A Guide to Upgrading, Repair and Maintenance. Crowood.

Levine, J., 2014. Anti-lock braking system - Early systems, in: Royal Enfield 70 Success Secrets - 70 Most Asked Questions On Royal Enfield - What You Need To Know. Emereo Publishing.

Nunney, M.J., 1992. Anti-lock brakes and traction control, in: Light and Heavy Vehicle Technology. Newnes, pp. 572–580. doi:http://dx.doi.org/10.1016/B978-0-7506-0477-2.50034-0

Ramsden, J.M., Field, H., Lambert, M., Wilson, M., Hofton, A. (Eds.), 1975. Dunlop Aviation is 50. Flight Int. 607–608.

Reynolds, J., 1990. Best of British bikes. Patrick Stephens.

Road Test, 1971. Computerized Braking. Road Test 38–43.

Robert Bosch GmbH, 2015. Technical evolution of motorcycle ABS [WWW Document]. URL http://www.bosch-motorcycle.com/en/de/fahrsicherheit_fuer_zweiraeder/motorrad_abs/technische_evolution_von_motorrad_abs/technische_evolution_von_motorrad_abs.html (accessed 5.1.15).

Robert Bosch GmbH, 2013. Mobility Solutions: Milestone for two-wheeler safety [WWW Document]. URL http://www.bosch-presse.de/presseforum/details.htm?txtID=6534&tk_id=108&locale=en (accessed 5.1.15).

Robert Bosch GmbH, 2003a. Bosch History. Bosch Hist. Mag. 1–35.

Robert Bosch GmbH, 2003b. 25th Bosch ABS anniversary [WWW Document]. URL http://www.bosch.com/assets/en/company/innovation/theme03.htm

Severson, A., 2009. Mark of Success: The Lincoln Continental Mark Series [WWW Document]. Ate Up with Mot. - Portraits Automob. Hist. URL http://ateupwithmotor.com/model-histories/lincoln-continental-mark-iii-iv-v/

Smith, M.A., King, H.F. (Eds.), 1954. Dunlop Maxaret Anti-Skid Unit for New High-Performance Aircraft. Flight Aircr. Eng. 2–3.

Smith, M.A., King, H.F. (Eds.), 1953. Non-Skid Braking - The Maxaret Automatic Control: What It Is and What It Does. Flight Aircr. Eng. 587–588.

Smith, M.A., King, H.F. (Eds.), 1951. Civil Aviation News... Flight Aircr. Eng. LIX, 296.

Smith, M.A., King, H.F., Gunston, W.T., Ramsden, J.M., Casey, R. (Eds.), 1961. Dunlop's Aviation Jubilee. Flight Aircraft, Spacecraft, Missiles 159–160.

Smith, M.A., Ramsden, J.M., Taylor, H.A., Casey, R. (Eds.), 1967. Special feature: Paris Show Guide. Flight Int. 847.

Starks, H.J.H., 1968. Physics and road safety - Braking and stability of vehicles. Crowthorne.

Veloso, F., Fixson, S., 2001. Make–Buy Decisions in the Auto Industry: New Perspectives on the Role of the Supplier as an Innovator. Technol. Forecast. Soc. Change 67, 239–257. doi:http://dx.doi.org/10.1016/S0040-1625(00)00092-5

3. Pattern

3.1. Pattern data

Date	Remarks	Source
1801	"Humphry Davy demonstrates the principle of what became fuel cells. […]The concept of a fuel cell had effectively been demonstrated in the early nineteenth century by Humphry Davy."	(Fuel Cell Today, 2015)
1838	"This was followed by pioneering work on what were to become fuel cells by the scientist Christian Friedrich Schönbein in 1838."	(Fuel Cell Today, 2015)
1839	"The development of the fuel cell technology can be dated back to 1839, when Sir William Grove designed the first working fuel cell (Mytelka & Boyle, 2008)." "William Grove, a chemist, physicist and lawyer, is generally credited with inventing the fuel cell in 1839. Grove conducted a series of experiments with what he termed a gas voltaic battery, which ultimately proved that electric current could be produced from an electrochemical reaction between hydrogen and oxygen over a platinum catalyst." "In 1839, the Welsh judge, Sir William Grove, presented the first fuel-cell battery, in which he was able to generate an electrical current from hydrogen and oxygen by reversing the process of electrolysis (Grove, 1839)."	(Mytelka and Boyle, 2008) (Fuel Cell Today, 2015) (Marscheider-Weidemann et al., 2009, p. 348)
1889	"Charles Langer and Ludwig Mond develop Grove's invention and name the fuel cell. […]The term fuel cell was first used in 1889 by Charles Langer and Ludwig Mond, who researched fuel cells using coal gas as a fuel. Further attempts to convert coal directly into electricity were made in the early twentieth century but the technology generally remained obscure."	(Fuel Cell Today, 2012)
1932	"In 1932, Cambridge engineering professor Francis Bacon modified Mond's and Langer's equipment to develop the first AFC but it was not until 1959 that Bacon demonstrated a practical 5 kW fuel cell system."	(Fuel Cell Today, 2012)
1950s	"The modern history of the proton exchange membrane fuel cell (PEMFC)[i] started in the early 1950s, when a number of companies and institutions began PEMFC development. They included Aerojet Company, General Electric (GE), National Carbon Company, the Patterson-Moos Division of the Universal Winding Company, and Pittsburgh Consolidation Coal"	(Behling, 2013, p. 425)
1950s	"General Electric invents the proton exchange membrane fuel cell."	(Fuel Cell Today, 2015)
1954, 1955-60	"The third research line [of GE's fuel cell research programme] focused on a different type of electrolyte than had been used before or was used by others in that period. The researchers Grubb and Niedrach advanced and explored the idea of using a membrane in which ionised groups were fixed so that it would be capable of exchanging oppositely charged ions. This research on the 'ion-exchange-membrane cell' started in 1954 (Bacon, 1969) and a first cell of 0,02 Watt was constructed. Research would continue between 1955 and 1960 during which a fuel battery of 15 Watt was build (Liebhafsky and Cairns, 1968)."	(Schaeffer, 1998, p. 356)
1954-55	"GE had the most ambitious program and in 1954 GE researchers Willard T. Grubb and Leonard Niedrach started research on the "ion-exchange membrane cell." They invented the first PEMFC in June 1955,[2] which generated 0.02 W.[1] GE's PEMFC was simpler in design and operation than Grove's original fuel cell [i.e. William Grove – the inventor of the fuel cell] and seemed almost elegant.[3] While Grove's cell used a corrosive sulfuric acid bath as the electrolyte, Grubb's fuel cell was made of all solid materials."	(Behling, 2013, p. 425)
1958	"Three years later [i.e. 1958], Niedrach devised a way of depositing platinum onto the fuel cell,[4] which accelerated electrochemical reactions and resulted in a	(Behling, 2013, p. 425)

	significantly higher efficiency. The improvements made through the combined efforts of Grubb and Niedrach produced the "Grubb-Niedrach fuel cell." GE used the PEMFC in research programs with the US Navy's Bureau of Ships (Electronics Division) and the US Army Signal Corps.[5] Although the cell was compact and portable, it was highly expensive to produce."	
1959	"Francis Bacon demonstrates a 5kW alkaline fuel cell [i.e. AFC]."	(Fuel Cell Today, 2015)
1959 [presumably]	"At around the same time, Harry Karl Ihrig fitted a modified 15 kW Bacon cell to an Allis-Chalmers agricultural tractor [researcher's note: presumably 1959]. Allis-Chalmers, in partnership with the US Air Force, subsequently developed a number of fuel cell powered vehicles including a forklift truck, a golf cart and a submersible vessel."	(Fuel Cell Today, 2015)
1959	"A 20 horsepower [AFC] system operating on hydrogen was installed in a tractor and demonstrations of the tractor plowing up a Milwaukee golf course were given in the fall of 1959."	(Sandstede et al., 2010, p. 195)
late 1950s	"A lucky break came to GE's PEMFC effort in the late 1950s when the US National Aeronautics and Space Administration (NASA) asked GE to play a major role in the US manned space program. NASA's Mercury Program (1958-1963) flew men into space in a capsule that was battery powered.[6] NASA needed options other than heavy batteries for its second manned program, Gemini (1962-1966), which would fly men into space for much longer periods.[7] Gemini was designed to test man and equipment for space flights up to 2 weeks in preparation for the third critical manned spaceflight program, the Apollo Lunar-Landing Mission (1963-1972)."	(Behling, 2013, p. 425)
late 1950s, early 1960s	"In the late 1950s and early 1960s NASA, in collaboration with industrial partners, began developing fuel cell generators for manned space missions. The first PEMFC unit was one result of this, with Willard Thomas Grubb at General Electric (GE) credited with the invention. Another GE researcher, Leonard Niedrach, refined Grubb's PEMFC by using platinum as a catalyst on the membranes."	(Fuel Cell Today, 2012)
1960s	"NASA first uses fuel cells in space missions."	(Fuel Cell Today, 2015)
1963	"In 1963, GE produced the first prototype PEMFC for NASA using the "Grubb-Niedrach fuel cell."[10] […] Two 1 kW modules were to provide primary power for each of the 12 Gemini missions. […] Gemini missions 1 through 4 flew with batteries instead of fuel cells.[12] GE redesigned their cells, and the new cells, despite malfunctions and poor performance on Gemini 5, adequately served for the remaining Gemini missions. Nevertheless, performance and lifetimes of the Gemini fuel cells were limited by the sulfonated polystyrene membrane used at that time."	(Behling, 2013, pp. 425–426)
1965	"Originally, PEFCs were developed for use in space, and were first employed in orbit aboard US Gemini V spacecraft in 1965." "The Grubb-Niedrach fuel cell was further developed in cooperation with NASA, and was used in the Gemini space programme of the mid-1960s."	(Maeda, 2003, p. 1) (Fuel Cell Today, 2012)
1965	"In 1965, Siemens equipped a boat with a 500W [alkaline] fuel cell according to their approach (see Figure 48).[186] Later they built 6 kW units (see Figure 49) for the propulsion of a submarine.[216]"	(Sandstede et al., 2010, p. 184)
1965	"[1965] Shell researchers in the UK had developed a 40-cell 300W [DMFC] module[289] with an acid electrolyte for methanol and air (see Figure 56)."	(Sandstede et al., 2010, p. 200)
1966 [presumably]	"By the mid-1960s, AFC batteries had been built. Figure 43 shows a forklift produced in 1966 with a 1.5kW hydrogen/oxygen fuel cell, which had a peak performance of 5 kW."	(Sandstede et al., 2010, p. 182)
1966	"[….] the world's first fuel cell electric vehicle, the GM Electrovan of 1966, was developed by General Motors based on alkaline fuel cells and fuel storage in the form of cryogenic hydrogen and oxygen"	(Eberle et al., 2012, p. 8780)
1966	"The GM Electrovan used a fuel cell produced by Union Carbide, which was fueled by both super-cooled liquid hydrogen and liquid oxygen. […] The Electrovan had	http://www.hydrogencarsnow.com/gm-electrovan.htm

	one large tank for the hydrogen and one for the oxygen and contained 550-feet of piping throughout the rear of the vehicle, turning this 6-seat van into a 2-seater with barely enough room for 2 passengers. […]The Electrovan also had a range of 120 miles, which was not too shabby for 1966. Because of safety concerns, the Electrovan was only used on company property, where it had several mishaps along the way. From the outset, the idea was to use a Corvair as the first hydrogen fuel cell vehicle and call it Electrovair. But, GM soon discovered that a leak with the electrolyte used caused "brilliant fireworks", plus it weighed 550 lbs. and needed to be housed in a larger vehicle. There was also the incident of the exploding hydrogen tank, which injured no one but sent pieces flying a quarter of a mile, which was of great concern and extra safety precautions needed to be taken to insure that no one working on the project was injured."	
1967	"In 1967, General Motors designed a first operational fuel-cell-powered electric vehicle, which was a six-passenger electrovan, using liquid hydrogen. It had a top speed of 105 km/h and a driving range of 200 km."	(Ball et al., 2009, p. 256)
1967	"Union Carbide's Karl Kordesch rides his alkali fuel cell motorcycle in 1967."	http://americanhistory.si.edu/fuelcells/alk/alkmain.htm
mid-1960s	"NASA believed fuel cells were the best option, and so a massive infusion of funds was directed at developing space-qualified fuel cells. Annual funding reached more than $20 million (in 1990 dollars) during the mid-1960s.[8] • NASA awarded two contracts to develop fuel cells to power the Gemini spacecraft, one to GE and one to United Technologies Corporation (UTC). They were selected to develop PEMFCs and alkaline fuel cells (AFCs), respectively.[9]"	(Behling, 2013, p. 425)
1968	"In 1968, […] (DuPont) developed an advanced membrane, Nafion, which had excellent thermal, chemical, oxidative, and mechanical stability, and seemed perfect for fuel cells.[14]"	(Behling, 2013, p. 426)
1968, 1984	"GE used Nafion in 1968 for the Biosatellite mission. […]By then, NASA had selected the alkaline fuel cell for use in the Apollo program. There had been a perception within NASA that the polymer electrolyte was intrinsically resistive and that the requirement for a higher power density fuel cell system for Apollo could be better met by the alkaline fuel cell. This, for all practical purposes, put the SPFC on the shelf for space applications for the next 20 years. With the exception of limited work under the sponsorship of Los Alamos National Laboratory, solid polymer fuel cell technology lay dormant until about 1984."	(Prater, 1990, p. 239)
1969	"In 1969, GE used Nafion in its second PEMFC system, a 350 W module that flew in three Biosatellite spacecraft (1966-1969), which NASA built to assess the effects of spaceflight on living organisms.[15]"	(Behling, 2013, p. 426)
n.d.	"GE next developed a 3 kW flight-qualified module for a Navy high-altitude Balloon program. This unit demonstrated a power density more than five times greater than GE's Gemini fuel cells."	(Behling, 2013, p. 426)
1970s	"Several German, Japanese and US vehicle manufacturers and their partners began to experiment with FCEV in the 1970s, increasing the power density of PEMFC stacks and developing hydrogen fuel storage systems."	(Fuel Cell Today, 2012)
1970s	"[…] initiated research projects to develop more efficient forms of energy generation in the 1970s. One result of this was important advances in PAFC technology, in particular in stability and performance. There were significant field demonstrations of large stationary PAFC units for prime, off-grid power in the 1970s, including a 1 MW unit developed by IFC. Funding from the US military and electrical utilities enabled developments in MCFC technology, such as the internal reforming of natural gas to hydrogen. The use of an established natural gas infrastructure was a key advantage in developing fuel cells for large stationary prime power applications."	(Fuel Cell Today, 2012)
mid-	"GE by the mid-1970s developed PEM water electrolysis technology and began	(Behling, 2013, p. 426)

1970s, 1987	work on the U.S. Navy Oxygen Generating Plant.[5] The British Navy adopted this technology in the 1980s for its submarine fleet" [researcher's note: in the late 1980s, as reported by Prater (1990, p. 247)]	
1980s	"Substantial technical and commercial development continued in the 1980s, notably in the area of PAFC. A bright future for the technology was widely predicted around this time for stationary applications and buses. […]Several experimental large stationary PAFC plants were built, but saw little commercial traction in the 1980s."	(Fuel Cell Today, 2015)
1980s	"Also in the 1980s, research, development and demonstration (RD&D) work continued into the use of fuel cells for transport applications. The US Navy commissioned studies into the use of fuel cells [researcher's note: not specific as to what type of fuel cells were used] in submarines where highly efficient, zero-emission, near-silent running offered considerable operational advantages."	(Fuel Cell Today, 2015)
1983	"In 1983 the Canadian company Ballard began research into fuel cells, and was to become a major player in the manufacture of stacks and systems for stationary and transport applications in later years."	(Fuel Cell Today, 2015)
1983	"In 1983, the DND awarded a contract to a small start-up firm to develop PEMFCs, according to the then Chairman and CEO of the firm.[16] The DND wanted the small firm [i.e. the Vancouver-based start-up Ballard Power Systems] to produce a low-cost PEM fuel cell that could run on impure hydrogen produced by reforming a liquid fuel like methanol.[17] […] Ballard Power Systems, which was soon to make history in successfully advancing PEMFC technology and applying it for practical applications."	(Behling, 2013, p. 427)
1983	"The Canadian firm Ballard Power Systems launched full-scale PEFC development in 1983 with funding from Canada's Department of National Defense […]"	(Maeda, 2003, p. 1)
1984	"Under the DND contract, Ballard began PEMFC research in 1984.[19]"	(Behling, 2013, p. 427)
1984	"In 1984, nonetheless, GE […] made a strategic decision to leave the fuel cell business."	(Behling, 2013, p. 426)
1985-86	"In 1985, Ballard demonstrated the ability to run PEMFCs on fuel gas by using a selective oxidation process after the fuel reformer […] Ballard constructed several 72 W demonstration stacks in 1986.[1]"	(Behling, 2013, p. 427)
1986	"In 2 years [after 1984], Ballard succeeded in developing an 8-cell stack that produced 130 W, considerably higher than the 50-100 W specified in the DND contract.[17] By mid-1986, it had succeeded in creating a 12-stack version capable of producing 280 W."	(Behling, 2013, p. 427)
1987, late 1980s	"[…] Ballard Power Systems […] in 1987 demonstrated the potential for high power density by incorporating Dow membranes in their fuel cells. Around the same time, US Los Alamos National Laboratory showed that cells could be manufactured with reduced amounts of platinum. It was at this point that the global race by the private sector to develop PEFCs started."	(Maeda, 2003, p. 1)
1987	"In addition to advancing the state of the technology, Ballard is committed to commercializing solid polymer fuel cells. To that end, in 1987 Ballard delivered a 2 kW hydrogen/oxygen fuel cell consisting of two-54 cell MK 4 stacks containing Nafion electrolytes to Perry Energy Systems in Florida. The unit was housed in a container 1 ft in diameter and 2 ft long and was intended to power an unmanned submersible. Shortly thereafter, Ballard delivered an identical unit to the U.K. Royal Navy for evaluation. The Perry unit has since been retrofitted with a single MK 5 Nafion-based stack in place of the two MK 4 stacks. The upgraded unit can provide up to 4.5 kW in the same volume as the original unit. This MK 5 unit provides the entire power requirements for a two-man submersible, which is now undergoing sea trials."	(Prater, 1990, p. 247)
1988	"Over the next several years, Ballard developed ever more powerful and smaller PEMFC stacks, establishing itself as the world leader in PEMFC technology. "	(Behling, 2013, p. 427)
1988	"The program went so well that in 1988 several 2 kW stacks were delivered to	(Behling, 2013, p. 427)

	military and civilian customers.[1]"	
1989	"In July 1989, Perry Energy successfully incorporated Ballard's 2 kW power plant into the first commercial fuel cell-powered submarine.[20] The boat was a two-man observation submersible."	(Behling, 2013, p. 427)
1990s	"Large stationary fuel cells are developed for commercial and industrial locations."	(Fuel Cell Today, 2015)
1990s	"Attention turned to PEMFC and SOFC technology in the 1990s, particularly for small stationary applications. These were seen as offering a more imminent commercial possibility, due to the lower cost per unit and greater number of potential markets - for example backup power for telecoms sites and residential micro-CHP. In Germany, Japan and the UK, there began to be significant government funding devoted to developing PEMFC and SOFC technology for residential micro-CHP applications."	(Fuel Cell Today, 2015)
1990s	"Companies other than automakers, such as Ballard, continued PEMFC research for automotive and stationary clean power. Ballard went on to supply PEMFC units to Daimler and Ford."	(Fuel Cell Today, 2015)
1990s	"Significant advances in DMFC technology occurred around the same time [i.e. 1990s], as PEMFC technology was adapted for direct methanol portable devices. Early applications included portable soldier-borne power and power for devices such as laptops and mobile phones. MCFC technology, first developed in the 1950s, made substantial commercial advances in the 1990s, in particular for large stationary applications in which it was sold by companies such as FuelCell Energy and MTU. SOFC technology also underwent substantial developments in terms of power density and durability for stationary applications."	(Fuel Cell Today, 2012)
1990	"In 1990, Ballard demonstrated an independent methanol-air PEMFC brassboard power plant. The 4 kW, 28 V DC methanol-air power plant was developed for the Canadian DND as a portable field generator."	(Behling, 2013, p. 427)
1990, 1993, 1995	"In 1990, Canada's Federal Department of Energy Mines and Resources, the Canadian Province of British Columbia, and the Federal Department of Energy Mines and Resources implemented a government-industry cost-share program to develop a PEMFC-powered bus. Ballard was chosen as the prime contractor and it started to develop PEMFC stacks up to 5 kW.[1] The bus was to seat 20 passengers, and the Canadian government reportedly invested a total of $4.84 million.[21] In 1993, Ballard introduced the world's first PEMFC bus built by New Flyer, which drove on the streets of Vancouver.[17] The 32 ft, low-floor transit bus, P1, was powered by 90 kW Ballard stacks.[19] […I]n June 1995, Ballard introduced its Phase Two P2 bus, a full-size prototype ZEV powered by a 205 kW fuel cell engine. It had a range of 250 miles before requiring refueling.[19] The P2 bus was based on a 40 ft New Flyer Model 40 lF bus.[22]"	(Behling, 2013, p. 428)
1992	"[S]etting out in 1992 to create fuel cell cars […] [1992] Toyota begins comprehensive development – from materials, components and systems to control and production technology."	(Toyota Motors, 2004, pp. 6, 8)
1997	"The first [hydrogen-powered] bus was the Ballard p1 and was released in 1993. "	(Ball et al., 2009, p. 257)
1994	"In April 1994, Daimler surprised the world with its first New Electric Car (NECAR) incorporating an improved version of the Ballard stack that was used in the P2 bus.[25] The NECAR, which was subsequently named the NECAR 1 to distinguish itself from succeeding NECARs, was a boxy cargo van, based on the MB-180 van. The van was powered by 12 Ballard fuel cells stacks, which collectively generated 50 kW and produced 60 hp.[17] With this vehicle, Daimler proved to the world audience the basic suitability of the fuel cell technology as an electric vehicle propulsion system.[25]"	(Behling, 2013, p. 428)
1992, mid-	"Notably, the Japanese automobile industry began such development [i.e. fuel-cell vehicles] in 1992, and built test vehicles in the middle of the 1990s."	(Maeda, 2003, p. 2)

1990s		
1996	"In May 1996, Daimler and Ballard demonstrated the world's first passenger car with PEMFC drive, the NECAR 2.[25] The six-passenger car, based on the V-Class minivan, had two 25 kW stacks and achieved a maximum speed of 68 mph and a range of 155 miles. NECAR 2's fuel cell system weighed only about 270 kg (600 lbs) and was much smaller in size and volume, about one-third of its predecessor."	(Behling, 2013, pp. 428–429)
1996	"[October 1996] In an exhibition parade in Osaka, Japan, Toyota demonstrates its in-house–developed FCHV, equipped with an original fuel cell stack and hydrogen-absorbing alloy tank [researcher's note: i.e. metal hydride hydrogen storage technology]."	(Toyota Motors, 2004, p. 8)
1997	"[…] wave for hydrogen-vehicle market introduction arose with announcements by Daimler and Toyota in 1997 of the production of fuel-cell cars in 2004 (see Fig. 8.1). After this, other car manufacturers joined the hydrogen race."	(Ball et al., 2009, p. 256)
1997-99	"Throughout 1997, the world was kept in awe by a series of astonishing developments at Ballard. In April 1997, Daimler said it was investing US$145 million to buy a one-quarter interest in Ballard, and announced it was investing $150 million in a joint venture with Ballard to create a new vehicle fuel cell engine company.[22] • The Ballard/Daimler/Ford alliance established three jointly owned companies: DBB Fuel Cell Engines (later named Xcellsis), Ecostar Electric Drive Systems, and Ballard Automotive.[19] […]The alliance would soon grow larger. Daimler and Ford brought in their affiliates. Ford brought in Mazda,Volvo, and Th!nk Nordic, a Norwegian electric car developer which it acquired in 1999. Daimler would bring in Chrysler, then US's third largest automaker, with which it merged in 1998.[27] The automakers would use Ballard fuel cell stacks to power their fuel cell cars, creating a powerful international fuel cell car alliance."	(Behling, 2013, p. 429)
1997	"[September 1997] Toyota unveils the world's first FCHV with an onboard methanol reformer."	(Toyota Motors, 2004, p. 9)
1998	"In 1998, the international competition to develop PEFCs was intensified when Daimler Chrysler, which partially capitalized Ballard with Ford Motor, announced that it would market in 2004 the world's first practical fuel cell car."	(Maeda, 2003, p. 2)
2000	"By the end of the century, all the world's major carmakers had active FCEV demonstration fleets as a result of these early efforts. The focus by then had shifted back to pure hydrogen fuel, which generates zero harmful tailpipe emissions."	(Fuel Cell Today, 2012)
2000	"Meanwhile, Ballard's first 110,000 ft^2 manufacturing plant for large-scale production of portable and automotive fuel cells was opened in Burnaby, British Columbia, in December 2000.[19]"	(Behling, 2013, p. 429)
early 2000s	"By the early 2000s, the global fuel cell race had begun in earnest. The Daimler/Ford/Ballard alliance virtually dominated media attention by their spectacular fuel cell development activities. They undoubtedly challenged and inspired others to enter the race. While it is not clear exactly when the global fuel cell race started, the establishment of the alliance between Daimler, Ford, and Ballard likely marked its beginning, and it grew in intensity until 2005. In the first few years, a large number of major automakers and bus manufacturers began FCV development and announced that they would commercialize their cars and buses in a few years. They made aggressive, large-scale investments in PEMFC technology R&D, energetically built up alliances, and unveiled their concept cars and prototypes with fanfare, creating major media around the world. […]In the early 2000, virtually every major automaker entered the fuel cell race. They rapidly unveiled increasingly sophisticated FCVs and buses and demonstrated them on public roads. Some automakers were announcing their near-term market entry dates. Others were somewhat more modest in their goals; they perhaps had less investment capital or more limited technical capabilities. Nonetheless, the	(Behling, 2013, pp. 429–430)

	participants seemed enthusiastic and committed."	
early 2000s	"There also were a large number of fuel cell bus development projects worldwide. Transit buses were viewed as well suited for fuel cell applications.[28] They had fixed routes, centralized fueling and maintenance infrastructures, and dedicated maintenance personnel. They were large enough to install fuel cell systems and hydrogen fuel tanks. Diesel transit buses were noisy and polluting, providing an opportunity to show off the advantages of fuel cells. There was even speculation that fuel cell buses might enter the commercial market much earlier than fuel cell passenger vehicles."	(Behling, 2013, p. 430)
2000s	"With subsequent advancements in membrane durability and system performance, PAFC were rolled out in greater numbers almost two decades later [than the 1980s] for large-scale combined heat and power applications."	(Fuel Cell Today, 2015)
2000s	"In the 2000s, the development of [hydrogen-powered] buses accelerated and many manufacturers got involved."	(Ball et al., 2009, p. 257)
2001	"[March 2001] […] Toyota announces the FCHV-3, equipped with a fuel cell stack featuring greatly advanced power output and a hydrogen absorbing alloy tank [researcher's note: i.e. metal hydride hydrogen storage technology]. [June 2001] […] Toyota announces the FCHV-4, equipped with high-pressure hydrogen tanks and the original Toyota FC Stack. Testing conducted on public roads in Japan and U.S. [June 2001] […] Toyota and Hino Motors co-develop a large, low-floor city bus, the FCHV-BUS1, which runs on compressed hydrogen. [October 2001] […] Toyota announces the FCHV-5, featuring an onboard CHF reformer, which derives hydrogen from "clean hydrocarbon fuel." […] Toyota and Daihatsu co-develop a compact fuel cell system suitable for minicar applications and announce the MOVE FCV-K-2, which runs on compressed hydrogen. Proving on public roads in Japan begins in February 2003."	(Toyota Motors, 2004, pp. 9–10)
2001	"February: Prototype fuel cell vehicle FCX-V3 equipped with a Honda FC Stack demonstrated at the California Fuel Cell Partnership in Sacramento, California July: Public road testing of the FCX-V3 begins in Japan […] Experiments with hydrogen production and fueling for fuel cell vehicles begin at Honda R&D Americas in California September: Prototype fuel cell vehicle FCX-V4 introduced"	(Honda Motor Company, 2015a)
2001	"At the end of 2001, however, the alliance [i.e. Ballard/DaimlerChrysler/Ford] announced that, in a transaction worth $547 million, Ballard had entirely taken over Xcellsis and Ecostar. At the same time, DaimlerChrysler and Ford raised their stakes in Ballard.[19]"	(Behling, 2013, p. 429)
2002	"The TOYOTA FCHV became the first-ever fuel cell vehicle to be certified by Japan's Ministry of Land, Infrastructure and Transport, making it available for limited marketing. […] [December 2002] […] Toyota begins limited marketing of the TOYOTA FCHV, a refinement of the FCHV-4. Two TOYOTA FCHVs are leased in the U.S. and four in Japan."	(Toyota Motors, 2004, pp. 8, 10)
2002	"March 1: Honda FCX-V4 granted certification by the Japanese Ministry of Land, Infrastructure and Transport March 3: Honda FCX-V4 serves as pace car for Los Angeles Marathon July 25: Honda FCX first fuel cell vehicle to receive US government certification for commercial use October 8: Agreement concluded with the City of Los Angeles to make Los Angeles the first US customer for a fuel cell car October 22: Introduction of the FCX prototype planned for commercial release within the year November 22: FCX granted certification by the Japanese Ministry of Land,	(Honda Motor Company, 2015b)

	Infrastructure and Transport December 2: FCX fuel cell vehicles delivered on the same day in Japan and the US"	
2002	"[September 2002] Toyota and Hino announce the completed development of the FCHV-BUS2, an improved version of the FCHV-BUS1. Public road testing begins in October 2003. […]In September 2002 certification was granted by the Ministry of Land, Infrastructure and Transport to begin testing on public roads. The FCHV-BUS2 began service as part of Tokyo's metropolitan bus fleet in August, 2003. Additional benefits include a smooth ride and extremely quiet operation inside and out."	(Toyota Motors, 2004, pp. 11–12)
2002-2003, 2004	"On December 2, 2002, Toyota began limited marketing with the delivery of two TOYOTA FCHVs in the U.S. (University of California, Irvine and Davis campuses) and four in Japan (Cabinet Secretariat; Ministry of Economy, Trade and Industry; Ministry of Land, Infrastructure and Transport; Ministry of the Environment). Delivery to corporate purchasers and local governments began in August 2003. Based on the FCHV-4 prototype, which accumulated over 130,000 kilometers of testing, the TOYOTA FCHV is a highly reliable and durable fuel cell hybrid vehicle that delivers a remarkable balance of high efficiency and luxuriously smooth, hushed cruising performance."	(Toyota Motors, 2004, p. 8)
2003	"[August 2003] FCHV-BUS2 becomes the first fuel cell bus to go into service as part of a municipal bus fleet in Japan." "FCHV-BUS2 municipal model became the first fuel cell bus to go into revenue service as part of a municipal fleet in Tokyo starting in August 2003.[96]"	(Toyota Motors, 2004, p. 12) (Behling, 2013, p. 448)
2003	"July 15: Honda becomes world's first automaker to supply a fuel cell vehicle to a private corporation […]FCX delivered to Iwatani International Corporation September 25: FCX vehicles delivered to the City of San Francisco […] October 10: Release of the Honda FC Stack, a next-generation fuel cell stack capable of power generation at temperatures as low as –20ºC […] Fuel cell stack Honda-manufactured"	(Honda Motor Company, 2015c)
2003	"The benefits of using fuel cells onboard trains are unclear, but a few countries have made attempts to develop a fuel cell rail system. In 2003, Japan Railway Technical Research Institute with government support tested a 100 kW fuel cell rail system made by Nuvera fuel cells following 2 years of development.[563] The project was mothballed or stalled through lack of interest or funds.[564]"	(Behling, 2013, p. 542)
2004	"The first four fuel cellepowered forklifts were deployed at a warehouse of Ozburn-Hessey Logistics in Smyrna, Tennessee, in 2004. Since then, fuel cellepowered material handling vehicles have become increasingly popular at warehouses, distribution centers, and factory floors in the United States and Canada."	(Behling, 2013, p. 530)
2004	"February 26: Public road testing in Hokkaido, Japan of Honda FC Stack-equipped FCX, proving the vehicle's cold-start and driving performance capabilities March 19: FCX first fuel cell vehicle test-driven at the office of the prime minister of Thailand April 5: Test drives of Honda FC Stack-equipped FCX begin on Yakushima Island (Japan) as part of the Yakushima Zero Emissions Project April: Honda FC Stack-equipped FCX test drives begin in the US July: Honda FC Stack-equipped FCX receives US government certification for commercial use November 16: Honda FC Stack-equipped FCX leased to New York State"	(Honda Motor Company, 2015d)
2005	"Daimler also announced that beginning in 2005, the new company would produce 100,000 fuel cell engines annually. This was a remarkable figure, considering that the company, the world's 15th largest auto manufacturer, made only 700,000 passenger cars a year at that time. Moreover, 8 months later, Ford Motor Company announced that it would join the alliance and invest $420 million in the venture.[26]"	(Behling, 2013, p. 429)
2005	"Hyundai Motor Co. unveiled its second-generation fuel cell vehicle, the Tucson	http://www.hydrogen-

	FCEV, The Tucson FCEV is Hyundai's first hydrogen-powered vehicle taking part in fleet operations to begin in the first quarter of 2005. Hyundai's second-generation fuel cell vehicle is dramatically improved in almost every way. The Tucson FCEV has a driving range double that of Hyundai's first-generation vehicle, the Santa Fe FCEV. Maximum speed and power have both increased to improve the overall performance. In a major technology breakthrough, the Tucson FCEV is one of the first fuel cell vehicles capable of starting in freezing temperatures. Testing has proven that the vehicle is capable of starting after being subjected to -20 degrees Celsius temperatures for five days. Other technical advancements including a higher output fuel cell and a new lithium ion polymer battery. "These advances in our fuel cell electric vehicles are exciting steps forward for our program," said Kim Sang-Kwon, president of research and development for Hyundai-Kia Motors. "The Tucson FCEV is proof that Hyundai has significantly improved efficiency and quality control in the manufacturing process." With this working model, Hyundai will be taking its fuel cell technology "to the fleets" and will begin fleet testing in just three months. Fleets will eventually operate out of AC Transit of Oakland, Calif., Hyundai American Technical Center and Southern California Edison. The fleet testing phase of Hyundai's fuel cell research and development program is supported by a grant from the U.S. Department of Energy (DOE)."	motors.com/hyundai-tucson-hybrid-fcev.html
2007	"In 2007, a little over one hundred hydrogen buses were used in various cities around the world."	(Ball et al., 2009, p. 257)
2007	"Fuel cells began to become commercial in a variety of applications in 2007, when they started to be sold to end-users with written warranties and service capability, and met the codes and standards of the markets in which they were sold. As such, a number of market segments became demand driven, rather than being characterised by oversupply and overcapacity. In particular, thousands of PEMFC and DMFC auxiliary power units (APU) were commercialised in leisure applications, such as boats and campervans, with similarly large numbers of micro fuel cell units being sold in the portable sector in toys and educational kits. Demand from the military also saw hundreds of DMFC and PEMFC portable power units put into service for infantry soldiers, where they provided power to communications and surveillance equipment and reduced the burden on the dismounted solider of carrying heavy battery packs."	(Fuel Cell Today, 2015)
2007	"Fuel cells begin to be sold commercially as APU and for stationary backup power."	(Fuel Cell Today, 2015)
2007	"According to Butler (2008), the number of fuel-cell cars in the world at the end of 2007 was around one thousand. Considering the geographic distribution of vehicle development and construction, Europe is the predominant region of fuel-cell vehicle manufacturing, with more than half of the market share, followed by North America with a fifth and Asia (largely Japan) with around a quarter. Europe's high market share is mainly accounted for by Daimler […]. Considering the deployment of fuel-cell vehicles, at the time of writing, North America and Europe had the lion's share, close to 50% each, with Asia taking up the remainder (Butler, 2008)."	(Ball et al., 2009, p. 256)
2008	"Honda begins leasing the FCX Clarity fuel cell electric vehicle." "TOCHIGI, Japan , June 16, 2008– American Honda Motor Co., Inc., announced five of the first customers for its advanced new FCX Clarity hydrogen fuel cell-powered vehicle and also provided details of the world's first fuel cell vehicle dealership network in the United States. The announcements were made during a ceremony for the start of FCX Clarity production at the world's first dedicated fuel cell vehicle manufacturing facility in Japan. Film producer Ron Yerxa will take delivery of the first FCX Clarity in July. The remaining four early adopters for Honda's next-generation fuel cell vehicle are	(Fuel Cell Today, 2015) http://world.honda.com/news/2008/4080616First-FCX-Clarity/index.html

	author and actress Jamie Lee Curtis and her filmmaker husband Christopher Guest; business owner and car enthusiast Jim Salomon; actress Laura Harris; and Jon Spallino, already the world's first retail fuel cell vehicle customer, who has been leasing the current generation FCX since 2005. Yerxa, Harris and Spallino attended the event in Japan."	
	"TOKYO, Japan, July 2, 2008– Honda Motor Co., Ltd. unveiled the Japan model of its FCX Clarity fuel cell vehicle, which will also be displayed at the Environmental Showcase at the G8 Hokkaido Toyako Summit that begins July 7, 2008. Leasing in Japan is scheduled to begin November 2008. Initially, leases are to be limited to government agencies and certain corporate customers. […]"	http://world.honda.com/news/2008/4080702FCX-Clarity/index.html
	"TOKYO, Japan, November 25, 2008– Honda Motor Co., Ltd. began leasing the FCX Clarity fuel cell vehicle in Japan, delivering the first vehicle to the Ministry of the Environment. This transaction follows directly upon a completed lease to the Ministry of the FCX fuel cell vehicle, predecessor to the FCX Clarity. Initially, Honda plans to lease the FCX Clarity in Japan only to governmental agencies and certain corporate entities. Honda has leased the vehicle in the US since July 2008. [….] The combined sales plan for Japan and U.S. calls for about 200 units within three years."	http://world.honda.com/news/2008/4081125FCX-Clarity/index.html
2008-2012	"TORRANCE, Calif., U.S.A., July 25, 2008– American Honda Motor Co., Inc., announced that Ron Yerxa and Annette Ballester took delivery of their hydrogen fuel cell-powered FCX Clarity on Friday, July 25, 2008 at Honda of Santa Monica, one of three dealerships in Southern California that are part of the first fuel cell vehicle dealership network. Yerxa and Ballester are the world's first FCX Clarity customers and the first of approximately 200 customers who will lease the vehicle in the United States and Japan over the next three years, with the vast majority of vehicles being leased in Southern California."	http://world.honda.com/news/2008/4080725FCX-Clarity/index.html
2008	"Honda is responsible for the development of the world's first fuel cell car (Honda FCX) to be certified for regular commercial use by the U.S. EPA and California Air Resources Board; the first deployment of a fuel cell car with a fleet customer; and the first individual retail customer for a fuel cell vehicle."	http://world.honda.com/news/2008/4080616First-FCX-Clarity/index.html
2008	"Worldwide, there were close to 200 hydrogen refuelling stations in operation at the time of writing (see www.netinform.net/h2/h2station s an d Huleatt-James, 2008). There are three leading geographical regions where hydrogen refuelling stations are found: North America, Europe and Eastern Asia, especially Japan. In the USA, there were about 65 operating hydrogen stations (compared with 170000 gasoline stations) concentrated in the north-eastern parts of the country (Chicago, New York) as well as in the metropolitan areas of California. In Japan, there were about 20 operating hydrogen refuelling stations at the time of writing, with the highest density in the area of Tokyo. In Germany, there were 21 operating hydrogen refuelling stations, which is the highest number in Europe; this compares with about 16 000 conventional refuelling stations in Germany (and about 1500 fuelling stations selling biodiesel and close to 800 natural gas stations). There are also some interesting projects in China around Beijing and Shanghai, as well as in Singapore and near New Delhi in India. Important demonstration projects for testing a hydrogen infrastructure are the California Fuel Cell Partnership (CaFCP), the Clean Energy Partnership (CEP) in Berlin and Hamburg and the already-mentioned HyFLEET:CUTE initiative for hydrogen buses."	(Ball et al., 2009, p. 259)
2008	"In August 2008, Hamburg launched the FCS Alsterwasser, a fuel cell-powered 100-passenger inland waterway tourist vessel.550 The vessel suffered a fire in 2010, but was back in service in June 2011.[551] Cause of the fire allegedly was traced to incorrectly connected batteries. The vessel has two 50 kW (67 hp) proton motor fuel	(Behling, 2013, p. 542)

	cells powering a 100 kW (134 hp) hybrid electric propulsion system with lead acid batteries. Using fuel cells as propulsion for inland waterway craft such as Hamburg's Alsterwasser is a logical first step leading toward more deployments. However, the application of fuel cells for propulsion in ships in the open ocean would require further technological maturity and development of capabilities that could withstand rough open-ocean conditions."	
2009	"In November 2009 Tokyo Motor show, Intelligent Energy and Suzuki presented the Suzuki Burgman fuel cell scooter.[544] Improved on the Crosscage fuel cell motorbike, the Burgman Fuel Cell Scooter was equipped with the latest version of Intelligent Energy's fuel cell power systems. Fuel was provided via a cylinder of hydrogen and gave a riding range of 217 miles, comparable to a conventional Burgman scooter. […]"	(Behling, 2013, p. 542)
late 2000s [presumably]	"In transport applications, the greatest commercial activity occurred in the materials handling segment, where there is a strong business case for their use in place of the incumbent technology, lead acid batteries. Fuel cell buses have been commercially available for several years and their usefulness has been well demonstrated. […] Fuel cell cars are currently only available for lease;"	(Fuel Cell Today, 2015)
2010	"In September 2009, Daimler presented a significantly advanced Mercedes-Benz B-Class F-Cell, which had a range of 248 miles and a top speed of 106 mph.[364] […] At the beginning of 2010, Daimler started to lease up to a total of 200 B-Class F-Cell vehicles.557 In June 2011, three B-Class F-Cell vehicles completed a 5-month trip around the globe, covering 18,641 miles,366 which convinced Daimler that the technology was now ready for mass production."	(Behling, 2013, p. 512)
2010	"During the 18 years from 1993 to December 2010, at least 86 new fuel cell buses were built. It appears that there were three peaks in fuel cell bus development during this time, which occurred in 2001, 2006, and 2010. For the first several years until 2001, only a few new fuel cell buses were developed each year. In 2001, six new fuel cell buses were introduced, the highest number to date. This was followed by 5 years of rather slow, deliberate development. Then, in 2006, 11 new fuel cell buses were built, nearly double the 2001 peak. Following another period of slow development, 14 new fuel cell buses were introduced in 2010, the highest number so far (Fig. 7.6). None of these peaks can be attributed to market demand. More likely, the increased rate of new bus introductions was due to major government bus demonstration projects that occurred in Europe, the United States, and elsewhere around."	(Behling, 2013, pp. 525–527)
2011	"According to the chart by Fuel Cell 2000, as of July 2011 at least 2220 forklifts or other material handling vehicles have been deployed in the North America since 2004.[491] Although the number was insignificant until 2008, it grew to 386 in 2009, 16 times greater than the number in 2008. In 2010, 646 forklifts were deployed, nearly double that of the previous year. In 2011, 1003 were deployed or are planned to be deployed; a 55 percent increase over 2010 (Fig. 7.7)."	(Behling, 2013, pp. 530–531)
2009	"In November 2009 Tokyo Motor show, Intelligent Energy and Suzuki presented the Suzuki Burgman fuel cell scooter.[544] […] In March 2011, the fuel cell scooter obtained Whole Vehicle Type Approval, which certified the scooter design as safe to use on public roads without having to be inspected and tested individually.[549]"	(Behling, 2013, p. 542)
2011	"CEP is Europe's leading fuel cell vehicle and hydrogen infrastructure demonstration project, bringing together expertise from vehicle manufacturers, infrastructure and energy companies, and the German Government. CEP is designed to prepare the ground for market entry of hydrogen mobility in Europe. Honda has been running fuel cell electric vehicles on European roads since 2009 and will support CEP activities with 2 FCX Clarity fuel cell electric vehicles. Ken Keir, Executive Vice President of Honda Motor Europe said, "Honda firmly believes that hydrogen fuel cell electric vehicles are the ultimate solution in reducing CO2 emissions from road transportation. Participation within CEP with the ground	http://world.honda.com/news/2011/c110519Clean-Energy-Partnership/index.html

	breaking FCX Clarity will demonstrate the viability of fuel cell technology and will also support the essential development of a European hydrogen refuelling infrastructure." Honda joins the Partnership at the same time as the industrial gas supply company, Air Liquide, demonstrating CEP's value in bringing together vehicle manufacturers and energy companies to support the development of hydrogen based mobility in Europe."	
2011	"Both Plug Power and Ballard have indicated reduced sale activities for fuel cell forklifts since June 2011."	(Behling, 2013, p. 540)
2012 [presumably]	"Daimler and Honda are leasing fuel cell electric vehicles (FCEVs) in California, and the other automakers have vehicles on the road in various states, including New York and Connecticut. Toyota announced it will place more than 100 of its FCHV-adv fuel cell vehicles at universities, private companies and government agencies in both California and New York. Most major auto manufacturers anticipate that commercial sales of fuel cell vehicles will begin in 2015. Fuel cell buses operate in daily revenue service in California, Texas, Connecticut, Delaware, as well as internationally, with more on the way. [not PEMFCV] In Europe, fuel cell auxiliary power units (APUs) are being sold as an optional accessory to power electronics in "caravans", or campers, when parked in remote locations or campsites."	(FuelCells.org, 2012)
2013	"Hyundai is providing 17 for fleet customers in the cities of Copenhagen, Denmark and Skåne, Sweden. It delivered five to the U.K. as part of the London Hydrogen Network Expansion project and two to Air Liquide in France. After 2015, with lowered vehicle production costs and further developed hydrogen infrastructure, Hyundai plans to begin sales of hydrogen FCEVs to individual customers."	(Curtin and Gangi, 2013, p. 30)
2013	"The Tucson Fuel Cell began mass production for the US market in April 2014 at the Ulsan, Korea assembly plant that also manufactures the Tucson gasoline-powered CUV. Hyundai began production of the ix35 Fuel Cell (the Tucson's counterpart in Europe) at Ulsan in January 2013; the first complete car rolled off the assembly line on 26 February 2013."	http://www.greencarcongress.com/2014/06/20140611-tucson.html
2013	"The ix35 Fuel Cell unveiled at the ceremony will be one of 17 destined for fleet customers in City of Copenhagen, Denmark and Skåne, Sweden. The Municipality of Copenhagen, as part of its initiative to be carbon-free by 2025, will be supplied with 15 ix35 Fuel Cell vehicles for fleet use, according to an agreement that was announced in September 2012. Two ix35 Fuel Cell vehicles will be supplied to Skåne, Sweden. "Assembly-line production of fuel cell vehicle marks a crucial milestone in the history of the automobile industry not just in Korea, but throughout the world," Mang Woo Park, mayor of Ulsan city, said in his congratulatory message. "By supplying more hydrogen refueling stations to support the eco-friendly fuel cell vehicles produced, we will make Ulsan the landmark for eco-friendly automobiles." Hyundai plans to build 1,000 ix35 Fuel Cell vehicles by 2015 for lease to public and private fleets, primarily in Europe, where the European Union has established a hydrogen road map and initiated construction of hydrogen fueling stations. […] Built with proprietary technology, Hyundai's ix35 Fuel Cell is powered by hydrogen. A fuel cell stack converts the hydrogen into electricity, which turns the vehicle's motor. The only emission generated by the ix35 Fuel Cell is water. Hyundai's ix35 Fuel Cell boasts drivability and performance similar to that of the petrol ix35. […]The ix35 Fuel Cell is the result of 14 years and several hundred million euros of research by hundreds of engineers at Hyundai's fuel cell R&D center in Mabuk, Korea. The car has logged more than 2 million miles of road tests in real-world conditions in Europe, Korea and the U.S."	http://www.autoblog.com/2013/02/26/first-production-hyundai-ix35-fuel-cell-vehicle-prepped-for-gene/

2013	"Daimler AG, Ford Motor Co, and Nissan Motor Co. are developing a "common fuel cell system" with plans to build 100,000 FCEVs between them, to start selling in 2017. Honda and General Motors are working to develop a next-generation fuel cell system and hydrogen storage technologies by 2020. Toyota and BMW aim to develop a complete FCEV system by 2020. Volkswagen is working with Ballard"	(Curtin and Gangi, 2013, p. 30)
2014	"The model will initially be supplied to government and private fleets and Hyundai plans to begin commercial sales of the model in its domestic market starting from June, with initial production of 1,000 FCEVs. The automaker expects sales of the model to total around 40 units this year. The model currently has a price tag of KRW150 million (USD144,400), but it will benefit from about KRW60 million (USD57,707) in subsidies currently offered by the South Korean government on purchases of such eco-friendly vehicles. In the long run, the automaker says that the price will eventually come down once it begins mass production of the vehicle. […]Commenting on the issue of safety, the executive revealed that, "The model received 27 safety certificates, which attests to its high standard of reliability and safety," as the automaker prepares to launch the Tucson FCEV in overseas markets. Hyundai expects the model to be sold in Europe and leased in California (United States) during the second half of 2014. […]Hyundai was awarded its first leasing contract for a hydrogen-powered fuel-cell vehicle by the European Commission-backed Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in October 2011, to be presented to EU decision-makers and the general public at a number of demonstration drives and public events in Brussels and other locations across Europe. Hyundai delivered 15 Tucson ix35 FCEVs to the city of Copenhagen in Denmark during mid-2013 and the other initial recipient country was Sweden, where two ix35 FCEVs were shipped to Skåne county. The automaker also supplied 10 pilot models to the Danish government, and this was followed by an agreement with Norway's Hydrogen Operation (Hyop) to supply fuel-cell vehicles and support Oslo's pilot project to employ hydrogen-fuelled vehicles for public agencies, companies, and taxis. The model was chosen for the second year in a row during 2013 by the FCH JU to demonstrate the real-world benefits of hydrogen fuel-cell technology. Such endorsements and offerings will help Hyundai boost sales in the European Union as it targets fleets. This is because many global markets have already mapped out a plan to deploy hydrogen vehicles and are simultaneously working towards supporting infrastructure."	https://technology.ihs.com/498893/
2014	"Hyundai thus is first out the gate with the next wave of "mass-produced" fuel cell vehicles. In this context, "mass-produced" means that the fuel cell vehicle is assembled on the same line at Ulsan, Korea, as the conventional Tucson, rather than hand-assembled. Volumes will initially be low: in the hundreds, said Gil Castillo, senior US group manager for Hyundai's alternative vehicle program. Hyundai is initially offering the Tucson Fuel Cell to customers in the Los Angeles/Orange County region for a 36-month term at $499 per month, with $2,999 down. This includes unlimited free hydrogen refueling in the area, and free maintenance. "When we spoke with customers about fuel cell vehicles, many wondered about the cost of hydrogen. To ease those concerns as the hydrogen refueling network builds out, we decided that covering this cost for these early adopters was appropriate, and consistent with how we like to treat our customers." —Dave Zuchowski, president and CEO, Hyundai Motor America"	http://www.greencarcongress.com/2014/06/20140611-tucson.html
2014 [presumably]	"Hyundai is also partnering with Enterprise Rent-A-Car to make the vehicle available to consumers at select locations in the Los Angeles/Orange County region."	(Curtin and Gangi, 2013, p. 30)

2015	"Powertrain […] Fuel Cell Type: Proton Exchange Membrane […] The Tucson Fuel Cell has passed numerous on-road tests for safety and durability conducted over an accumulated distance of 2 million miles. Plus, with features like its high-strength carbon fiber-wrapped fuel tank and several safety systems designed to protect passengers and first responders, the Tucson Fuel Cell is as safe as any vehicle on the road. […] The Tucson Fuel Cell is currently being leased in Southern California. It will be available in other regions as fueling infrastructure becomes available. […] The Tucson Fuel Cell is only available for a 36-month lease, $499 per month and $2,999 due at lease signing. This will include all maintenance, fuel, carpool lane access, and "At Your Service" concierge service for regularly scheduled complimentary maintenance and vehicle service. […] at this time the vehicle is only available for lease. In addition, there is no purchase option at the end of the lease. […]The Tucson Fuel Cell will initially be available only in Southern California due to the current availability of public hydrogen refueling stations. In the future, the Tucson Fuel Cell will be available in other areas as public refueling infrastructure expands beyond Southern California. […] […]The Tucson Fuel Cell will qualify for a $5,000 rebate under California's Clean Vehicle Rebate Project. Please go to http://energycenter.org/clean-vehicle-rebate-project for more information. […] servicing the Tucson Fuel Cell is similar to the conventional vehicle. Typical items include servicing the brakes, replacing the cabin air filter, replacing the coolant, etc. […] The Hyundai fuel cell has one major difference compared to its competitors: The Hyundai fuel cell uses near ambient air pressure to provide oxygen to the fuel cell stack compared to fuel cell systems that use compressed air. Compressing air requires additional energy. Hyundai's design results in low parasitic loss in the oxygen supply, which leads to high fuel efficiency and reduces power consumption by 50 percent. This setup also reduces noise in the cabin. […] Hyundai Fuel Cell vehicles have been subjected to extensive safety testing, including destructive and non-destructive evaluations at the component, system and vehicle level. There are many internal safety mechanisms to ensure the safety of the vehicle. All Hyundai vehicles complete a rigorous crash test program before they are ever driven on public roads. The Tucson Fuel Cell has undergone crash tests for offset-frontal, side and rear impact, as well as fire tests. Also, there are several impact sensors. In event of a crash, the sensors stop the release of hydrogen from the tanks. […]Like any fuel, hydrogen requires proper handling and a safe system design for production, storage and usage. Hydrogen, if properly handled, is as safe as gasoline, diesel or natural gas—and in some instances even safer. For decades, hydrogen has been shipped and used safely in the United States for use in everything from welding to hydrogenated peanut butter. […] if there's a leak in a storage tank, the hydrogen dissipates quickly into the air, without polluting. […] Yes, the tanks are very safe. There have been no reported cases of catastrophic failure of a storage tank. If a leak occurs, there is almost no risk of explosion because hydrogen is lighter than air and rises immediately, minimizing the risk of explosion. If the Tucson Fuel Cell is stored in an enclosed space, four onboard hydrogen sensors are designed to detect leaks and sound an alarm."	https://www.hyundaiusa.com/tucsonfuelcell/

3.5. Market actors and factors

Year(s)	Market actors and factors before invention	Description of their influence or role	Source
late 1800s	knowledge of the technology; competition from alternative technologies;	"Despite this, the principle of the fuel cell was not able to be developed into a technically mature process for a long time. The main reasons, apart from insufficient knowledge of the electrochemical processes involved, were material problems. Around the turn of the century, the dynamo generator (1866, Siemens), combustion engines (1876 Otto; 1897, Diesel) and the gas turbine (1900, Stolze) were successfully introduced to the market, so there was little interest on the part of industry in the development of an electrochemical generator. More intensive work on the basic principles of fuel cells was only begun around 1950 in England, then Germany and the USA."	(Marscheider-Weidemann et al., 2009, pp. 348–349)
Year(s)	Market actors and factors innovation phase	Description of their influence or role	Source
1960s	customers; commercial need;	"In the 1960s, there was little commercial interest in fuel cells, so the government-sponsored programs were very important for the development of fuel cells."	(Sandstede et al., 2010, p. 207)
1960s	in-competition: AFC vs. PEMFC;	"In 1963, GE produced the first prototype PEMFC for NASA using the "Grubb-Niedrach fuel cell."[10] […] 7.2.1. GE PEMFCs Fail Manned Space Mission in the late 1960s Power density was a low 38 mW/cm2 at a voltage of 0.83 V per cell. Water was removed with a wick in each cell, which was not very reliable. Gemini missions 1 through 4 flew with batteries instead of fuel cells.[12] GE redesigned their cells, and the new cells, despite malfunctions and poor performance on Gemini 5, adequately served for the remaining Gemini missions. Nevertheless, performance and lifetimes of the Gemini fuel cells were limited by the sulfonated polystyrene membrane used at that time. • NASA decided to use AFCs developed by UTC for both the command and lunar modules for the Apollo missions, as did designers of the Space Shuttle a decade later."	(Behling, 2013, pp. 425–426)
n.d.	IFC / UTC Power	"International Fuel Cells (IFC, later UTC Power) developed a 1.5 kW AFC for use in the Apollo space missions. […] IFC subsequently developed a 12 kW AFC, used to provide onboard power on all space shuttle flights."	(Fuel Cell Today, 2012)
n.d.	technology scalability; technology scope; in-competition;	The technical advantages of PEFCs over the other types include lower operating temperature and higher energy density. Consequently, it is technologically possible to miniaturize PEFCs and use them for not only industrial purposes, but also a broad range of applications that includes fuel cell cars and portable batteries.	(Maeda, 2003, p. 1)
mid-1960s	governmental research subsidies	"NASA believed fuel cells were the best option, and so a massive infusion of funds was directed at developing space-qualified fuel cells. Annual funding reached more than $20 million (in 1990 dollars) during the mid-1960s.[8]"	(Behling, 2013, p. 425)
mid-1960s	Shell	"From the mid-1960s, Shell was involved with developing DMFC, where the use of liquid fuel was considered to be a great advantage for vehicle applications."	(Fuel Cell Today, 2012)
1966	accidents	"Once, the on-board hydrogen tank exploded, though it isn't clear if this was due to combustion or over-pressurization. In either case, the resulting force was enough to send shrapnel over a quarter-mile radius, prompting	http://blog.hemmings.com/index.php/2013/08/29/ca

		the decision to limit testing of the Electrovan to GM's own property instead of extending it to public roads. The journalists on hand for its reveal in October of 1966 weren't even allowed to drive it, as it was perceived to be far too complex (and potentially dangerous) to leave in untrained hands. […] Though the demonstration was impressive (with some equating it to GM's own space program), the Electrovan project was scrapped soon after its reveal. As each of the 32 fuel cells used a considerable amount of platinum in its construction, duplicating the build would have been cost-prohibitive for all practical purposes. Then there was the complexity of the laboratory-grade fuel cell system used in the Electrovan, as well as the total absence of a hydrogen infrastructure […]" "There was also the incident of the exploding hydrogen tank, which injured no one but sent pieces flying a quarter of a mile, which was of great concern and extra safety precautions needed to be taken to insure that no one working on the project was injured."	rs-of-futures-past-1966-gm-electrovan/#sthash.ezfBG5t6.dpuf http://www.hydrogencarsnow.com/gm-electrovan.htm
1960s-70s	GE' investment in R&D	"GE maintained a high level of inhouse investment in PEMFC R&D even after the Gemini project was over. GE reportedly spent $8.5 million of its own money over the 1960s and 1970s.[13]"	(Behling, 2013, p. 426)
1968	knowledge of technology; new high-tech product; performance improvements; supplier of components (DuPont);	"In 1968, the EI DuPont de Nemours and Company (DuPont) developed an advanced membrane, Nafion, which had excellent thermal, chemical, oxidative, and mechanical stability, and seemed perfect for fuel cells.[14] In 1969, GE used Nafion in its second PEMFC system, a 350 W module that flew in three Biosatellite spacecraft (1966-1969), which NASA built to assess the effects of spaceflight on living organisms.[15]"	(Behling, 2013, p. 426)
1970s	oil crisis; macro-economic factor; government policies;	"The oil crisis prompts the development of alternative energy technologies including PAFC [i.e. phosphoric acid fuel cells]. [….]. The 1970s was also the era of the OPEC oil embargoes, which led governments, businesses and consumers to embrace the concept of energy efficiency. […] Concerns over oil availability in the 1970s led to the development of a number of one-off demonstration fuel cell vehicles, including models powered by hydrogen or ammonia, as well as of hydrogen-fuelled internal combustion engines. […]Prompted by concerns over energy shortages and higher oil prices, many national governments and large companies initiated research projects to develop more efficient forms of energy generation in the 1970s."	(Fuel Cell Today, 2015)
1970s	regulatory environment; environmental concerns;	"The 1970s saw the emergence of increasing environmental awareness amongst governments, businessesand individuals. Prompted by concerns over air pollution, clean air legislation was passed in the United States and Europe. This ultimately mandated the reduction of harmful vehicle exhaust gases and was eventually adopted in many countries around the world. […] Clean air and energy efficiency [note: see 1970s oil crisis] were to become two of the principal drivers for fuel cell adoption in subsequent decades, in addition to the more recent concerns about climate change and energy security."	(Fuel Cell Today, 2015)
1979	Ballard	"Ballard was founded in 1979 under the name Ballard Research to conduct research and development in high-energy lithium batteries.[18] Under the DND contract, Ballard began PEMFC research in 1984.[19]"	(Behling, 2013, p. 427)

1959-1980	performance improvements; new high-tech product; supplier of components (DuPont); central actor (GE);	"As DuPont continued to make improvement in Nafion, GE made significant progress in improving the performance of PEMFC units. In 21 years between 1959 and 1980, GE's cell performance increased 160-fold from 5 to 800 W/ft2 (from 5.4 to 861 mW/cm2) (Table 7.1)."	(Behling, 2013, p. 426)
Year(s)	Market actors and factors market adaptation phase	Description of their influence or role	Source
1983-84, mid-1980s	technology transfer; technology license; GE; Siemens AG; UTC;	"In 1984, nonetheless, GE apparently made a strategic decision to leave the fuel cell business. During 1983-1984, it licensed the basic know-how for PEMFCs to Siemens AG in Germany. In the mid-1980s, GE transferred PEMFC and electrolysis technology to UTC-Hamilton Standard."	(Behling, 2013, p. 426)
early 1980s	governmental research subsidies; research objectives;	"In the early 1980s, the Government of Canada was thinking about developing domestic PEMFC capabilities. Canada clearly believed that PEMFC technology could be further improved and decided to have a Canadian firm improve the cost and performance of PEMFC technology and develop a PEMFC capability to tolerate impure hydrogen as fuel."	(Behling, 2013, pp. 426–427)
early 1980s	technology transfer	"Sometime in the early 1980s, Ottawa's Department of National Defense (DND) purchased from NASA the PEMFC technology developed by GE that had lain dormant for some time."	(Behling, 2013, p. 427)
1983	government research subsidy; research objectives; Canadian DND; Ballard;	"In 1983, the DND awarded a contract to a small start-up firm to develop PEMFCs, according to the then Chairman and CEO of the firm.[16] The DND wanted the small firm [i.e. the Vancouver-based start-up Ballard Power Systems] to produce a low-cost PEM fuel cell that could run on impure hydrogen produced by reforming a liquid fuel like methanol.[17]"	(Behling, 2013, p. 427)
1986, late 1980s	performance improvements; new high-tech product; Ballard	"Ballard quickly demonstrated outstanding technical progress. In 2 years [after 1984], Ballard succeeded in developing an 8-cell stack that produced 130 W, considerably higher than the 50-100 W specified in the DND contract.[17] By mid-1986, it had succeeded in creating a 12-stack version capable of producing 280 W. […]Over the next several years, Ballard developed ever more powerful and smaller PEMFC stacks, establishing itself as the world leader in PEMFC technology."	(Behling, 2013, p. 427)
1985-1988	performance improvements; new high-tech product; Ballard; technology configuration	"In 1985, Ballard demonstrated the ability to run PEMFCs on fuel gas by using a selective oxidation process after the fuel reformer to convert CO to CO2 external to the cell. Ballard constructed several 72 W demonstration stacks in 1986.[1] In 1988, it made a two-and-one-half to threefold improvement in maximum power density of PEMFCs, from 800 to 2000-2500 W/ft^2."	(Behling, 2013, p. 427)
late 1980s	government research subsidy; Canadian DND; Ballard;	"In view of the successful completion of its first contract, the DND awarded Ballard a second contract to support further development.[17]"	(Behling, 2013, p. 427)
1980s	knowledge of the technology; new high-tech product (commercial feasibility);	"The low operating temperature made it possible to achieve compact, high density designs, and it became economically feasible to commercialize the cells. Because of these advances, PEFC developers started eyeing markets that could not be served by phosphoric acid fuel cells–namely, automobile, residential, and compact commercial applications."	(Maeda, 2003, pp. 1–2)

1987	knowledge of the technology; production;	"Performance improvements have also been achieved with Nafion 117 […] a roughly 50% improvement in limiting current density in a single cell using the same Nafion 117 as the electrolyte. This improvement results from changes in the fabrication procedure for the membrane/electrode assembly."	(Prater, 1990, p. 244)
late 1980s, 1987-1988	external factors; suppliers (Ballard); knowledge of technology; natural resources; new high-tech product; performance improvements; product components;	"There were two external factors that likely contributed to Ballard's accomplishments: • In the 1980s, researchers at Los Alamos and Texas A&M showed that the amount of platinum required for the fuel cell could be reduced by a factor of 10. Their work likely convinced Ballard that low-cost PEM fuel cells were possible. • Also in the early 1980s, Dow Chemical was experimenting with a sulfonic polymer.[19] In 1987 and 1988, Ballard tested Dow's new membrane, which allowed the cell to produce four times the current compared to that of Nafion at the same cell voltage. Cell durability of over 10,000 h was also demonstrated.[19]"	(Behling, 2013, pp. 427–428)
n.d.	technology transfer	"Dow's new membrane was the most significant development since the introduction of Nafion by DuPont in 1968. Dow Chemical's rights to manufacture this membrane were subsequently transferred to DuPont,[19] and DuPont has continued to improve durability and performance of its membranes."	(Behling, 2013, p. 428)
1990	product developed to order; Ballard; commissioner (Canadian DND)	"In 1990, Ballard demonstrated an independent methanol-air PEMFC brassboard power plant. The 4 kW, 28 V DC methanol-air power plant was developed for the Canadian DND as a portable field generator."	(Behling, 2013, p. 427)
1990	new high-tech product; product development commission from government (Canada); Ballard;	"In 1990, Canada's Federal Department of Energy Mines and Resources, the Canadian Province of British Columbia, and the Federal Department of Energy Mines and Resources implemented a government-industry cost-share program to develop a PEMFC-powered bus. Ballard was chosen as the prime contractor and it started to develop PEMFC stacks up to 5 kW.[1] The bus was to seat 20 passengers, and the Canadian government reportedly invested a total of $4.84 million.[21]"	(Behling, 2013, p. 428)
early 1990s	Ballard; technology leadership;	"By the early 1990s, Ballard had become the global PEMFC leader. It was viewed worldwide as having established PEMFCs as the predominant fuel cell technology that would finally deliver the fuel cell's unfulfilled promise."	(Behling, 2013, p. 428)
n.d. [presumably 1990s]	environmental legislation in North America	"The toughening of environmental regulations in North America pressed automobile manufacturers operating in that market to establish long-term environmental strategies, and thus they set about developing fuel-cell vehicles."	(Maeda, 2003, p. 2)
1990s	government policies	"Government policies to promote clean transport also helped drive the development of PEMFC for automotive applications. In 1990, the California Air Resources Board (CARB) introduced the Zero Emission Vehicle (ZEV) Mandate. This was the first vehicle emissions standard in the world predicated not on improvements to the internal combustion engine (ICE) but on the use of alternative powertrains. Carmakers such as the then-DaimlerChrysler, General Motors, and Toyota, all of which had substantial sales in the US, responded to this by investing in PEMFC research. Companies other than automakers, such as Ballard, continued PEMFC research for automotive and stationary clean power."	(Fuel Cell Today, 2012)
early 1990s, 1991, 1993	supplier (Ballard); automotive manufacturers	"Inspired by Ballard's developments, nearly every major automaker in the world launched a program to build a PEM fuel cell vehicle (FCV).[23] The automotive world was beating a path to Ballard's door.[19] All of the former	(Behling, 2013, p. 428)

	(General Motors, Chrysler, Ford, Daimler-Benz)	"big three" US automotive manufacturers –General Motors, Chrysler, and Ford–were early customers of Ballard." In Europe, Daimler-Benz clearly was the most enthusiastic believer in Ballard's PEMFC capabilities. In 1993, Daimler-Benz and Ballard signed a 4-year joint venture agreement, to which Daimler committed $35 million.[24]"	
1991-92	in-house R&D; R&D strategy; Toyota;	"Since setting out in 1992 to create fuel cell cars, Toyota has made a point of keeping fuel cell development in-house. As the heart of a fuel cell vehicle, the fuel cell is no exception to Toyota's basic stance of developing core technologies on its own."	(Toyota Motors, 2004, p. 6)
1983	government research policy; subsidy;	"Under the "New Sunshine Plan," the Japanese government initiated in 1993 a program for research and development on PEFCs for use in transportation and commercial applications."	(Maeda, 2003, p. 2)
1996, 1998, 2007	Daimler-Benz, Daimler-Chrysler, Daimler	"In 1998, Daimler-Benz of Stuttgart, Germany, merged with Chrysler of the United States and renamed itself Daimler-Chrysler. In 2007, DaimlerChrysler sold Chrysler Division to Cerberus Capital Management of New York, a private equity firm and changed its name to Daimler. This book [i.e. (Behling, 2013)] will use the three names during the corresponding time periods; Daimler-Benz (or Daimler for short) for the period prior to 1998, DaimlerChrysler between 1996 and 2007, and Daimler for the period after 2007."	(Behling, 2013, p. 428)
late 1990s	macro-economic factors;	"Boosted by general optimism in high-technology industries, many fuel cell companies listed on stock exchanges in the late 1990s, only for prices to fall victim to the crash in technology stocks shortly after."	(Fuel Cell Today, 2012)
n.d.	government research policy; subsidy	"In Japan, industry-related organs of the government, perceiving the need to support automakers, electronics manufacturers, and other domestic industries, began actively pursuing policies aimed at supporting PEFC research and development and promoting the spread of PEFC use."	(Maeda, 2003, p. 2)
2000	customer segment (buses); social aspects; environmental concerns;	"Hydrogen buses (see Fig. 8.2) have their own development history, since in some cities authorities showed demand for them. They favoured the buses for their low pollution as well as for social reasons, such as raising public hydrogen awareness and promotion of further research. […] One important hydrogen bus demonstration project worth mentioning in Europe is the HyFLEET:CUTE initiative (HyFLEET:CUTE, 2007)."	(Ball et al., 2009, p. 257)
2000	technological configuration	"Today [i.e. in 2008], almost every car maker possesses its own prototypes and development experience. Different car manufacturers follow different design concepts, with regard to drive train, hydrogen storage or market segment to be addressed. Most of the prototypes developed after 2000 were fuel-cell vehicles rather than vehicles with internal combustion engines (an exception being, for example, BMW). The preferred storage option is for compressed gaseous hydrogen tanks, although liquid hydrogen storage can also be found.[6]"	(Ball et al., 2009, p. 256)
2000	R&D; Hyundai; partnerships;	"Hyundai formed its first fuel cell task force team in 2000 and by October of the same year, it unveiled the Santa Fe FCEV, its first prototype fuel cell vehicle. Hyundai has been an active member in the California Fuel Cell Partnership (CaFCP) in Sacramento, Calif. for five years [i.e. from 2000]. Past-generation Hyundai fuel cell vehicles have participated in numerous CaFCP Road Rallies and Michelin Challenge Bibendums where Hyundai has won gold and silver awards in a variety of categories."	http://www.hydrogen-motors.com/hyundai-tucson-hybrid-fcev.html
2000s	external factors; energy security; environmental concerns;	"The last decade was characterised by increasing concerns on the part of governments, business and consumers over energy security, energy efficiency, and carbon dioxide (CO2) emissions. Attention has turned once again to fuel cells as one of several potential technologies capable of	(Fuel Cell Today, 2012)

		delivering energy efficiency and CO2 savings while reducing dependence on fossil fuels.”	
2000s	funding; government policy / subsidy; demonstration projects;	“Government and private funding for fuel cell research has increased markedly in the last decade. There has been a renewed focus on fundamental research to achieve breakthroughs in cost reduction and operational performance to make fuel cells competitive with conventional technology. A good deal of government funding worldwide has also been targeted at fuel cell demonstration and deployment projects. The European Union, Canada, Japan, South Korea, and the United States are all engaged in high-profile demonstration projects, primarily of stationary and transport fuel cells and their associated fuelling infrastructure. The genuine benefits that fuel cell technology offers over conventional technologies has played a part in promoting adoption. “ “Moreover, the governments of major industrialized countries, including Japan, the United States, and European countries, started national fuel cell development programs to develop not only PEMFCs for transport applications but also stationary applications. They started anew or reinforced their existing measures to subsidize fuel cell development and nurture the business environment for the fuel cell industry. The governments and the fuel cell industries thus worked in tandem for a common goal of achieving global competitiveness and economic growth.”	(Fuel Cell Today, 2012) (Behling, 2013, pp. 429–430)
2000s	customers; knowledge of technology;	“The broader, technically informed public was also excited with the belief that PEMFC technology had come of age at last and they would be able to drive their FCVs soon.”	(Behling, 2013, p. 430)
2000s	customer segments	“For example, the value proposition that fuel cell materials handling vehicles offer in terms of extended run-time, greater efficiency and simplified refuelling infrastructure compared with their battery counterparts makes them attractive to warehouse operators. Tens of fuel cell buses were deployed in the mid-2000s as part of the HyFleet/CUTE project in Europe, China and Australia. Buses were, and still are, seen as a promising early market application of fuel cells due to their combination of high efficiency, zero-emissions and ease of refuelling, and due to the vehicles running on set routes and being regularly refuelled with hydrogen at their bases.”	(Fuel Cell Today, 2012)
2002	technology scope; new high-tech product; performance; potential of customer segment (public transport, heavy vehicles)	“The FCHV-BUS2 employs the same Toyota FC Stack as the TOYOTA FCHV. In fact, it uses two of these fuel cell stacks. From the sheer size of this vehicle you might imagine its response would be ponderous. But riding the FCHV-BUS2 soon ends any apprehension. Powerful motor torque assures particularly smooth and quiet acceleration”	(Toyota Motors, 2004, p. 13)
2002-2004	JHFC: automobile manufacturers, supply infrastructure actors	“A large project named JHFC is underway in Japan to investigate in detail the energy effectiveness, environmental burden and other aspects of fuel cell vehicle use. Toyota, Nissan, Honda, DaimlerChrysler, GM, Hino, Mitsubishi, and Suzuki are participating to collect basic data through fuel cell vehicle trials on public roads. Also participating are fuel producers who may supply hydrogen in either gas or liquid form at their fueling stations.”	(Toyota Motors, 2004, p. 18)
2002-2004	Honda	“[Honda FCX] [2002] Fuel cell stack Ballard-manufactured [2003, 2004, 2005] Fuel cell stack Honda-manufactured”	(Honda Motor Company, 2015d)
2002-2003,	testing; new high-	“Based on the FCHV-4 prototype [researcher’s note: leased to corporate	(Toyota Motors,

2004	tech product; performance;	and government actors], which accumulated over 130,000 kilometers of testing, the TOYOTA FCHV is a highly reliable and durable fuel cell hybrid vehicle that delivers a remarkable balance of high efficiency and luxuriously smooth, hushed cruising performance."	2004, p. 8)
2003	potential of customer segment (urban commuter)	"Jointly developed by Toyota and Daihatsu, the MOVE FCV-K-2 is a fuel cell hybrid that runs on hydrogen carried in a high-pressure tank. In January 2003, it became the first fuel cell minicar approved by Japan's Ministry of Land, Infrastructure and Transport for use on public roads. Road testing began in February 2003. Test data will be used to support further progress in developing the vehicle's potential as a vehicle for urban commuters."	(Toyota Motors, 2004, p. 14)
2004	knowledge of the technology (temperature-performance); geographical constraints (climate-suitability); new high-tech product (cost, reliability, durability, etc.); complementary services (servicing); recycling;	"Before fuel cell vehicles can be made available to everybody, a number of technical issues still need to be resolved. In addition to issues of safety and cruising distance, there is the problem that water produced by the fuel cell may freeze when the temperature dips to zero or below, thereby limiting climate suitability. Cost is another major "if." Popularization of fuel cell hybrid vehicles requires further progress in reliability, durability, servicing and recycling. Toyota is committed to tackling these technical issues to quickly bring fuel cell hybrid vehicles to maturity and make FCHV benefits available to the general public as soon as possible. […] When hydrogen and oxygen combine in the fuel cell to generate electricity, the chemical reaction also produces water. If temperatures drop to around -10°C or -20°C, this water may freeze inside the fuel cell itself or in the system's pumps and valves, causing difficulties when starting. This may appear a simple problem, but because it is closely related to the principle of fuel cell operation it is not an easy problem to solve."	(Toyota Motors, 2004, p. 15)
2004	knowledge of the technology; socio-cultural aspects (expected range); new high-tech product (range performance);	"The TOYOTA FCHV's current cruising range is about 300km (in the Japanese 10-15 test cycle), which is still far from satisfactory. To match the cruising distance of a gasoline engine vehicle, further improvements in fuel cell and system efficiency are needed and much more hydrogen must be carried on board. Instead of a high-pressure hydrogen tank, we could use a liquid hydrogen tank or a hydrogen-absorbing alloy. However, these are not in themselves solutions. Attaining higher storage efficiency is a difficult challenge that Toyota is facing with further development efforts, including the doubling of maximum tank pressure to 70MPa (about 700 bars)."	(Toyota Motors, 2004, p. 15)
2004	complementary products (hydrogen); infrastructure; environmental concerns;	"Although a hydrogen-powered fuel cell vehicle puts out no CO2 itself, CO2 is produced when hydrogen is made from fossil fuels. So if we intend to reduce CO2, we must go beyond tank-to-wheel efficiency and tackle well-to-tank efficiency as well. For example, coal is an abundant and economical natural resource, but making hydrogen from coal produces large amounts of CO2, so practical CO2 fixation technologies must be developed to separate, recover and store this carbon in the ground or elsewhere. In addition, while it is true that CO2 could be reduced if we used renewable energy sources such as solar power or biomass to make hydrogen, the quantity that can be supplied in this way is currently limited. Since hydrogen can be made from many sources, we need to consider production methods from a comprehensive viewpoint, including the economic, supply volume, and environmental (CO2) aspects."	(Toyota Motors, 2004, p. 17)
2004	new high-tech product; performance targets; competitive	"A conventional gasoline car's tank-to-wheel efficiency is 16% and its overall well-to-wheel efficiency is about 14%. In comparison, a hybrid vehicle like the Toyota Prius achieves 37% tank-to-wheel efficiency, more than double that of the conventional gasoline car, for 32% overall	(Toyota Motors, 2004, p. 16)

	technology;	efficiency (well to wheel), which is also more than double. The 88% well-to-tank efficiency stays the same for both types of vehicle. The TOYOTA FCHV has a high tank-to-wheel efficiency of 50%, more than triple that of a gasoline car, yet its overall efficiency (well to wheel) remains at 29%. This is because the efficiency with which we currently derive hydrogen from natural gas is still a low 58%. Therefore, Toyota believes that fuel cell hybrid vehicles require at least three times the overall (well-to-wheel) efficiency of gasoline cars if they are to fulfill their role of representing the next generation of automotive technology"	
2004	infrastructure; regulation (codes, standards, others); knowledge of the technology (hydrogen storage);	"To promote a smooth shift to a hydrogen-based society, we need the combined effort of all sectors of society, including the government. This is clearly the case when it comes to developing hydrogen manufacturing and storage technology, as well as building the hydrogen fueling station infrastructure. In our universities and technical schools we must invest in training new specialists. The establishment of codes and standards is another example of the kinds of issues that must be tackled in a comprehensive and multifaceted way by society as a whole. […] General public: Gaining understanding of a hydrogen-based society; promoting awareness"	(Toyota Motors, 2004, p. 18)
2004	performance as compared to gasoline engines; new high-tech product;	"Toyota's completely original fuel cell — the Toyota FC Stack — is a performance leader [researcher's note: view expressed by the company itself; perhaps indicative of 2004] among vehicular fuel cells worldwide, and is already on the verge of surpassing gasoline engines in power density."	(Toyota Motors, 2004, p. 6)
2004	customer segment (materials handling vehicle, North America)	"In recent years, PEMFC technology has been making rapid inroads into the material handling market, which includes forklifts, fork trucks, and other warehouse vehicles (so-called forklifts). These applications tend to be indoors where emissions must be controlled. The growth in deployment of forklifts probably is due to tangible economic and operational benefits over traditional technologies. The material handling equipment sector appears to be a niche where the advantages of fuel cells serve user needs so well that the cost disadvantages can be tolerated. Market growth is only occurring in North America, however, and is barely discernible elsewhere. […] Fuel cell-powered equipment have some attractive characteristics compared to the traditional material-handling equipment, which generally use propane and diesel internal combustion engines (ICE) or leadeacid batteries. Fuel cell material handling vehicles operate silently, with zero- or near zero-emissions, and offer faster refueling as well as significantly longer run times compared to their conventional counterparts.[490] Fuel cells also do not require lengthy recharging time or need large amounts of plant space for recharging equipment, as compared to battery-powered vehicles."	(Behling, 2013, p. 530)
2005	subsidy; knowledge of technology; new high-tech product; performance; temperature; manufacturing;	"The Tucson [2nd gen] FCEV has a driving range double that of Hyundai's first-generation vehicle, the Santa Fe FCEV. Maximum speed and power have both increased to improve the overall performance. In a major technology breakthrough, the Tucson FCEV is one of the first fuel cell vehicles capable of starting in freezing temperatures. Testing has proven that the vehicle is capable of starting after being subjected to -20 degrees Celsius temperatures for five days. Other technical advancements including a higher output fuel cell and a new lithium ion polymer battery. "These advances in our fuel cell electric vehicles are exciting steps forward for our program," said Kim Sang-Kwon, president of research and	http://www.hydrogen-motors.com/hyundai-tucson-hybrid-fcev.html

		development for Hyundai-Kia Motors. "The Tucson FCEV is proof that Hyundai has significantly improved efficiency and quality control in the manufacturing process." With this working model, Hyundai will be taking its fuel cell technology "to the fleets" and will begin fleet testing in just three months. Fleets will eventually operate out of AC Transit of Oakland, Calif., Hyundai American Technical Center and Southern California Edison. The fleet testing phase of Hyundai's fuel cell research and development program is supported by a grant from the U.S. Department of Energy (DOE)."	
n.d.	Toyota;	"The hybrid system proven in Toyota's Prius, the world's first mass-produced hybrid car, achieves its highly efficient operation through sophisticated energy management of a gasoline engine and battery. Toyota applied this hybrid technology to realize high efficiency in the TOYOTA FCHV as well. […]Power control unit [referring to Toyota FCHV 4] The "brain" of the hybrid system, this precisely manages fuel cell output and battery charging/discharging, in accordance with driving conditions."	(Toyota Motors, 2004, pp. 7, 8)
n.d.	government-industry partnership; drivers for technology innovation	"[…] Japan's circumstances, the direction of energy and environmental policies, and the distinctive qualities of fuel cell technology have all combined to make the development of this technology a matter of great priority for both industry and the government. These two players […] are sharing information and collaborating in development in an unprecedented manner. Under the government-industry partnership, the following factors are stimulating fuel cell development and driving innovation in this technology. • Driver 1: Energy efficiency • Driver 2: Reduced environmental impact • Driver 3: Diversification of energy supply, and petroleum alternatives • Driver 4: Distributed power generation • Driver 5: Industrial competitiveness"	(Maeda, 2003, p. 4)
2007	institutional aspects (codes, standards); government policies;	"Fuel cells began to become commercial in a variety of applications in 2007, when they started to be sold to end-users with written warranties and service capability, and met the codes and standards of the markets in which they were sold. As such, a number of market segments became demand driven, rather than being characterised by oversupply and overcapacity. […]In the past decade, PEMFC and DMFC have dominated the total market share in the portable, stationary and transport sectors. Their uptake by consumers has been facilitated by the development of codes, standards and government policies to lower the barriers to adoption; such as allowing methanol fuel cartridges on board aircraft and feed-in tariffs for fuel cell CHP installations."	(Fuel Cell Today, 2015)
2007	customer segments	"In particular, thousands of PEMFC and DMFC auxiliary power units (APU) were commercialised in leisure applications, such as boats and campervans, with similarly large numbers of micro fuel cell units being sold in the portable sector in toys and educational kits. Demand from the military also saw hundreds of DMFC and PEMFC portable power units put into service for infantry soldiers, where they provided power to communications and surveillance equipment and reduced the burden on the dismounted solider of carrying heavy battery packs."	(Fuel Cell Today, 2015)
2007	government policy / subsidy;	"A large-scale residential CHP programme in Japan helped stimulate commercial stationary PEMFC shipments. These units began to be	(Fuel Cell Today, 2015)

		installed in homes from 2009, and more than 13,000 such units have been installed to date.”	
n.d.	demonstration projects (US); accidents / events;	“Demonstration programmes for backup power systems in the USA gave further impetus to the stationary sector. This was also driven by practical concerns over the need for reliable backup power for telecoms networks during emergencies and rescue operations. The inadequacy of diesel generators was illustrated during the Gulf of Mexico Hurricane Katrina disaster, when many ran out of fuel, disrupting the telecoms network and hampering relief efforts.”	(Fuel Cell Today, 2015)
2007	infrastructure; customers;	“The company will need to carefully select customers, based on their proximity to the limited number of hydrogen refueling stations. The lack of infrastructure to produce, distribute and sell hydrogen fuel is among the major obstacles to the adoption of fuel cell vehicles.”	http://www.hybridcars.com/honda-fcx-clarity-hydrogen-home-refueling/
2007	knowledge of the technology; customers;	“Public knowledge of hydrogen technology is still relatively low (Fuhrmann and Bleischwitz, 2007). Many people still do not know the difference or have difficulties with separating the usage of hydrogen as a fuel from the fuel cell, which is a device to turn hydrogen into useful power. […] The consumer acceptance in the transport sector seems to be no barrier to the introduction of hydrogen. All analysed studies show that there is a great acceptance, but a low knowledge level for hydrogen technologies. Males and people with a higher education level seem to have a greater acceptance.”	(Ball et al., 2009, pp. 266, 268)
2008	knowledge of the technology; new high-tech product; performance	“Significant advances over Honda's previous generation FCX include a 25 percent increase in combined fuel economy to 72 miles/kg-H2* (74 mpg GGE <miles per gasoline gallon equivalent>) and a greater than 30 percent increase in driving range up to 280 miles*.”	http://world.honda.com/news/2008/4080725FCX-Clarity/index.html
2008	complementary services	“TOCHIGI, Japan , June 16, 2008– […] To provide its customers with outstanding sales and service support and as a critical step in advancing fuel cell vehicles in the real world, American Honda announced the establishment of the first network of dealers to facilitate the sales and service of fuel cell vehicles. The three Southern California Honda dealers are Power Honda Costa Mesa (Costa Mesa), Honda of Santa Monica (Santa Monica) and Scott Robinson Honda (Torrance). [….]American Honda is working with its dealer partners to implement processes for fuel cell vehicle lease, delivery and service support for the duration of their leases. Establishing a dedicated sales network and service infrastructure provides customers with the best balance of convenience and the highest quality of service. When the FCX Clarity requires periodic maintenance, customers will simply schedule a visit with their local FCX Clarity dealer. American Honda will perform all required work at its specialized fuel cell service facility in the greater Los Angeles area. Upon completion of the work, the dealer will return the vehicle to the customer.”	http://world.honda.com/news/2008/4080616First-FCX-Clarity/index.html
2008	sales criteria; complementary products; user needs	“The five customers announced today were among the very first people to share with Honda their passion for the environment and interest in the FCX Clarity, dating back to its debut as a concept model at the 2005 Tokyo Motor Show. The initial criteria for fuel cell vehicle ownership, including proximity to hydrogen refueling stations, driving patterns and vehicle needs, all played a part in Honda’s customer selection process.”	(Honda Motor Company, 2008)
2008	production system;	“TOKYO, Japan, June 16, 2008– Honda Motor Co., Ltd. announced that	http://world.hond

	Japan'	it has begun production of the new FCX Clarity fuel cell vehicle, with the first vehicle (U.S. specification) coming off the line. The FCX Clarity is produced at the Honda Automobile New Model Center (Takanezawa-machi, Shioya-gun, Tochigi Prefecture). A new dedicated fuel cell vehicle assembly line was established, which includes processes unique to a fuel cell vehicle such as the installation of the fuel cell stack and hydrogen tank. The fuel cell stack itself is produced at Honda Engineering Co., Ltd. (Haga-machi, Haga-gun, Tochigi Prefecture)."	a.com/news/2008/4080616New-FCX-Clarity/index.html
2009	knowledge of technology; regulatory aspects; safety standards; costs;	"Issues regarding hydrogen infrastructure itself[:] Storage technology: infrastructure, vehicle mounting and capacity, cost[;] Safety standards, regulatory issues[;] … Sustainable energy and hydrogen prices: high costs beyond electricity[;] R&D is needed to reduce costs further."	(Ishitani, 2010, p. 17)
2009	installed base	"There is resistance to up-front preparation of FCV hydrogen infrastructure, since there are no vehicles around yet are no vehicles around yet."	(Ishitani, 2010, p. 14)
2009	commercialization expectations	"[A]t the time of writing […m]ost car manufacturers currently see commercial production of fuel-cell cars around 2015."	(Ball et al., 2009, p. 256)
2009	educate customers	"Initially, leases are to be limited to government agencies and certain corporate customers. Numerous FCX Clarity events are to be held beginning in 2009 at which the public will have the opportunity to come in contact with the FCX Clarity and gain a greater appreciation of the appeal of fuel cell vehicles."	http://world.honda.com/news/2008/4080702FCX-Clarity/index.html
2009	Europe; institutional aspects;	"Honda has been running fuel cell electric vehicles on European roads since 2009 and will support CEP activities with 2 FCX Clarity fuel cell electric vehicles."	http://world.honda.com/news/2011/c110519Clean-Energy-Partnership/index.html
2009 [presumably]	technology acceptance; customers; knowledge of the technology	"So far, only a few studies exist to analyse the acceptance of hydrogen by the general public, most of which were conducted in European countries. Most of them focus on the transport sector, especially on public transport, such as buses and taxis. Studies that take into account the whole production line of hydrogen do not yet exist. […] No explicit studies concerning the perception of the security aspect of hydrogen have been made so far and it is only possible to draw conclusions from the overall attitude towards hydrogen technologies. […]To conclude, surveys generally show that there is a great acceptance, but a low knowledge level for hydrogen technologies. Males and people with a higher education level seem to have a greater acceptance. There is practically no opposition to the introduction of hydrogen as a fuel. However, more educational activities and possibilities for practical experience with hydrogen vehicles are critical measures to increase public acceptance."	(Ball et al., 2009, p. 266)
2009 [presumably]	regulations (standards, codes, etc.);	"Regulations, codes and standards must be internationally harmonised and consistent with the maximum extent. […] The development of internationally recognised regulations, codes and standards is vital not to impede the development of new hydrogen and fuel cell products and projects. An adequate level of standardisation and regulation is equally required in ensuring the safe deployment of hydrogen technologies in the market. Regulation and standards have to be put in place for the entire hydrogen supply chain, i.e., production, transportation and storage,	(Ball et al., 2009, pp. 267–268)

		hydrogen refuelling infrastructure, fuel-cell technologies and hydrogen-fuelled vehicles. If these aspects are not appropriately considered, RCS may become a barrier to the early introduction into the market and hydrogen systems may encounter resistance from insurers.[8] […] The establishment of internationally harmonised and consistent regulations, codes and standards is essential for the commercialisation of hydrogen-based products and systems."	
late 2000s	customer need; customer segments; developing countries; geographic considerations;	"The need for reliable on-grid or off-grid stationary power in developing countries also gave a boost to fuel cells. In the late 2000s, hydrogen and natural gas fuelled PEMFC units began to be sold in parts of India and east Africa to provide primary or backup power to mobile phone masts. The rapidity of mobile phone adoption in these regions means that the conventional grid infrastructure cannot keep pace with new power demands, or is too unreliable for an effective mobile network. Fuel cells provide a solution to this previously unmet need."	(Fuel Cell Today, 2012)
late 2000s [presumably]	subsidy; cost;	"Fuel cell buses have been commercially available for several years and their usefulness has been well demonstrated. However their cost, at around five times that of a diesel bus, plus the cost of hydrogen infrastructure means that they are only used where a city deems the environmental benefit to be worth the extra investment."	(Fuel Cell Today, 2012)
late 2000s [presumably]	knowledge of technology;	"Fuel cell cars are currently only available for lease; these vehicles are being made available by manufacturers to gain experience ahead of a commercial launch planned from 2015."	(Fuel Cell Today, 2012)
late 2000s	subsidy;	"Fuel cell forklifts were sold in large numbers between 2009 and 2010 due to ARRA and owing to the DoD purchases. After all, the ARRA incentives were highly attractive and virtually paid half the deployment cost. In 2011 (as of June 2011), however, 1003 forklifts were sold, and 921 units (92 percent) were sold without subsidies. In the aggregate, out of a total 2230 forklifts sold since 2004 thru June 2011, 1628 (73 percent) were sold independently of the ARRA subsidies."	(Behling, 2013, p. 540)
late 2000s [presumably]	suppliers; production;	"The supply chain has also been steadily growing alongside the increase in the number of fuel cell system manufacturers. There has been an expansion of the component supply chain and related services, from the manufacturers of MEA to fuel and infrastructure providers. Manufacturing capacity has tended to increase more rapidly than output. This is particularly true in North America, one of the leading regions for fuel cell manufacturing."	(Fuel Cell Today, 2012)
late 2000s	macro-economic aspects;	"The global economic recession of the late 2000s undoubtedly had negative effects for certain fuel cell companies. Limited credit availability and restrictions in government funding, as well as lack of profitability for organisations that were still mainly RD&D focused, caused a number of firms to go out of business. However, it gave other companies the impetus to become more commercially orientated and to pursue opportunities for revenue generation that could support further R&D in their core competencies. Since the recession, governments around the world have come to see fuel cells as a promising area of future economic growth and job creation and have invested further resources in their development, something fuel cell companies have not been slow to capitalise on. As many Western countries seek to rebalance their economies towards high-value manufacturing and environmental technologies, fuel cells seem poised to enter a period of sustained growth."	(Fuel Cell Today, 2012)
2010	infrastructure costs;	"Future tasks: Steady progress of regulations review, facilities costs	http://www.jari.or

	financial resources;	reduction / improvement of equipment efficiency”	.jp/portals/0/jhfc/data/seminor/fy2010/pdf/day1_E_09.pdf
n.d.	complemetary products & services	“With the sales of fuel cell forklifts in the U.S. growing every day, and with fuel cell buses and vehicles already on the road, several companies are focused on generating and dispensing hydrogen to service them. Large chemical companies such as Air Products and Linde are working with state agencies and companies to open hydrogen fueling stations, as well as dispensers at warehouses and forklift sites. Proton Onsite has joined with SunHydro to open a public station network on the East Coast. Smaller companies such as Pdc Machines and Avālence are also moving units to help increase and improve the hydrogen infrastructure.”	(FuelCells.org, 2012)
2011	Europe; subsidy; demonstration project; complementary products; infrastructure;	“CEP is Europe's leading fuel cell vehicle and hydrogen infrastructure demonstration project, bringing together expertise from vehicle manufacturers, infrastructure and energy companies, and the German Government. CEP is designed to prepare the ground for market entry of hydrogen mobility in Europe. Honda has been running fuel cell electric vehicles on European roads since 2009 and will support CEP activities with 2 FCX Clarity fuel cell electric vehicles. Ken Keir, Executive Vice President of Honda Motor Europe said, "Honda firmly believes that hydrogen fuel cell electric vehicles are the ultimate solution in reducing CO2 emissions from road transportation. Participation within CEP with the ground breaking FCX Clarity will demonstrate the viability of fuel cell technology and will also support the essential development of a European hydrogen refuelling infrastructure." Honda joins the Partnership at the same time as the industrial gas supply company, Air Liquide, demonstrating CEP's value in bringing together vehicle manufacturers and energy companies to support the development of hydrogen based mobility in Europe.”	http://world.honda.com/news/2011/c110519Clean-Energy-Partnership/index.html
2013 [presumably]	customer segments	“Transportation applications include motive power for cars, buses, and other fuel cell passenger vehicles, specialty vehicles, material-handling vehicles (e.g., forklifts) and APUs for highway and off-road vehicles. Some transportation applications, such as aircraft, locomotives, trucks, mining vehicles, cranes, marine vessels, golf carts, bikes, scooters, and water taxis, are still in an early stage of development […]”	(Behling, 2013, p. 511)
2013	complementary products & services; infrastructure; cost reductions; economies of scale;	“The strategy of leading automakers in Europe and the U.S. is to supply hydrogen fuel cell vehicles and establish refueling stations in order to prepare the market for mass production of hydrogen fuel cell vehicles. After 2015, with lowered vehicle production costs and further developed hydrogen infrastructure, Hyundai will begin manufacturing hydrogen fuel cell vehicles for consumer retail sales.”	https://technology.ihs.com/498893/
2013	cost reductions; knowledge of the technology; complementary services;	“Furthermore, modularization of fuel cell systems for the core part of the hydrogen fuel cell vehicle -- fuel cell stack, driving device and inverter -- enabled the engine to be downsized to match the size of a gasoline engine while improving productivity and making maintenance more convenient.”	http://www.autoblog.com/2013/02/26/first-production-hyundai-ix35-fuel-cell-vehicle-prepped-for-gene/
2014	institutional aspects; standards; complementary	“SAE taskforce completes two technical standards on hydrogen refueling; harmonizing the global infrastructure […] To support the impending roll-out of hydrogen fueling infrastructure	http://www.greencarcongress.com/2014/03/2014032

	products & services; infrastructure;	and Fuel Cell Electric Vehicles (FCEV), SAE International's Fuel Cell Standards Taskforce has completed two technical standards: SAE J2601, "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles"; and SAE J2799, "Hydrogen Surface Vehicle to Station Hardware and Software". The standards have been created to harmonize hydrogen fueling worldwide for both 35 MPa and 70 MPa pressures. […]Resources SAE J2601, "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles" SAE J2799, "Hydrogen Surface Vehicle to Station Hardware and Software" Jesse Schneider et al. "Validation and Sensitivity Studies for SAE J2601, the Light Duty Vehicle Hydrogen Fueling Standard" (SAE 2014-01-1990)"	6-j2601.html
2014	subsidy	"The South Korean government is supporting the effort with a plan already in place that offers up to KRW3.1 million (USD2,981) to consumers in the form of acquisition, registration, and individual consumption tax breaks [for FCEVs]. When purchasing FCEVs, consumers will also not have to buy the state bonds that are mandatory for all other vehicle purchases. The government is also offering preferential auto insurance policies for buyers of eco-friendly vehicles. The government recently set up a public-private body to stimulate the country's hydrogen sector, including the development of hydrogen cars and generators and the establishment of relevant infrastructure. Furthermore, the South Korean government is also planning to build 10 more refuelling stations by 2020, with 200 to be set up nationwide by 2025."	https://technology.ihs.com/498893/
2014	complementary products & services; hydrogen infrastructure	"However, infrastructure remains an issue and cannot be supported by the government in the long term. Hyundai is making a rapid breakthrough in the FCEV domain and its technology highlights Hyundai's growing prowess in the fuel-cell field and could lead to a bigger role for the automaker in the emerging global fuel-cell vehicle market. Although Hyundai expects to begin mass production of its new FCEV by the year-end, this technology is still very much in its infancy from a cost and refuelling network perspective and it will be some time before it gains mass acceptance."	https://technology.ihs.com/498893/
2014	US; infrastructure; complementary products & services;	"To support the development of the hydrogen infrastructure development, California approved a plan in October 2013 to develop up to 100 hydrogen refueling stations in the state over the next several years. […] Additionally, the California Energy Commission recently announced the proposed awarding of $44.5 million for the development of 28 new hydrogen stations (plus one mobile refueler), bringing the total number of hydrogen fueling stations (open, in-development, and proposed) to more than 50 stations."	http://www.greencarcongress.com/2014/06/20140611-tucson.html
2015	performance; knowledge of technology;	"[…] The Hyundai fuel cell has one major difference compared to its competitors: The Hyundai fuel cell uses near ambient air pressure to provide oxygen to the fuel cell stack compared to fuel cell systems that use compressed air. Compressing air requires additional energy. Hyundai's design results in low parasitic loss in the oxygen supply, which leads to high fuel efficiency and reduces power consumption by 50 percent. This setup also reduces noise in the cabin."	https://www.hyundaiusa.com/tucsonfuelcell/
2015	safety	"[…] The Tucson Fuel Cell has passed numerous on-road tests for safety	https://www.hyun

		and durability conducted over an accumulated distance of 2 million miles. Plus, with features like its high-strength carbon fiber-wrapped fuel tank and several safety systems designed to protect passengers and first responders, the Tucson Fuel Cell is as safe as any vehicle on the road. […] Hyundai Fuel Cell vehicles have been subjected to extensive safety testing, including destructive and non-destructive evaluations at the component, system and vehicle level. There are many internal safety mechanisms to ensure the safety of the vehicle. All Hyundai vehicles complete a rigorous crash test program before they are ever driven on public roads. The Tucson Fuel Cell has undergone crash tests for offset-frontal, side and rear impact, as well as fire tests. Also, there are several impact sensors. In event of a crash, the sensors stop the release of hydrogen from the tanks. […]Like any fuel, hydrogen requires proper handling and a safe system design for production, storage and usage. Hydrogen, if properly handled, is as safe as gasoline, diesel or natural gas—and in some instances even safer. For decades, hydrogen has been shipped and used safely in the United States for use in everything from welding to hydrogenated peanut butter. […] if there's a leak in a storage tank, the hydrogen dissipates quickly into the air, without polluting. […] Yes, the tanks are very safe. There have been no reported cases of catastrophic failure of a storage tank. If a leak occurs, there is almost no risk of explosion because hydrogen is lighter than air and rises immediately, minimizing the risk of explosion. If the Tucson Fuel Cell is stored in an enclosed space, four onboard hydrogen sensors are designed to detect leaks and sound an alarm."	daiusa.com/tucsonfuelcell/
2015	cost; leasing; complementary products & services; subsidy;	"[…] The Tucson Fuel Cell is only available for a 36-month lease, $499 per month and $2,999 due at lease signing. This will include all maintenance, fuel, carpool lane access, and "At Your Service" concierge service for regularly scheduled complimentary maintenance and vehicle service. […] at this time the vehicle is only available for lease. In addition, there is no purchase option at the end of the lease. […]The Tucson Fuel Cell will qualify for a $5,000 rebate under California's Clean Vehicle Rebate Project. Please go to http://energycenter.org/clean-vehicle-rebate-project for more information. […] servicing the Tucson Fuel Cell is similar to the conventional vehicle. Typical items include servicing the brakes, replacing the cabin air filter, replacing the coolant, etc."	https://www.hyundaiusa.com/tucsonfuelcell/
2015	market readiness; infrastructure; complementary products & services	"The A7 Sportback h‑tron quattro is a genuine Audi – at once sporty and efficient. Conceived as an e‑quattro, its two electric motors drive all four wheels," explained Prof. Dr. Ulrich Hackenberg, Member of the Board of Management for Technical Development at Audi. "The h‑tron concept car shows that we have mastered fuel cell technology. We are in a position to launch the production process as soon as the market and infrastructure are ready." [researcher's note: in 2013 Audi announced it was developing a PEMCV and that it would begin trials in August 2013 see http://www.autocar.co.uk/car-news/new-cars/fuel-cell-powered-audi-a7-development]	http://www.audi.com/com/brand/en/vorsprung_durch_technik/content/2014/11/audi-a7-sportback-h-tron-quattro.html

References (excl. direct links)

Ball, M., Wietschel, M., Seydel, P., 2009. Hydrogen today, in: Ball, M., Wietschel, M. (Eds.), The Hydrogen Economy: Opportunities and Challenges. Cambridge University Press, Cambridge, pp. 254–270.

Barbir, F., 2013. Fuel Cell Applications, in: Barbir, F.B.T.-P.E.M.F.C. (Second E. (Ed.), PEM Fuel Cells. Academic Press, Boston, pp. 373–434. doi:http://dx.doi.org/10.1016/B978-0-12-387710-9.00010-2

Behling, N.H., 2013. Chapter 7 - History of Proton Exchange Membrane Fuel Cells and Direct Methanol Fuel Cells, in: Behling, N.H.B.T.-F.C. (Ed.), Fuel Cells: Current Technology Challenges and Future Research Needs. Elsevier, pp. 423–600. doi:http://dx.doi.org/10.1016/B978-0-444-56325-5.00007-7

Curtin, S., Gangi, J., 2013. 2013 Fuel Cell Technologies Market Report. Washington, D.C.

Eberle, U., Muller, B., von Helmolt, R., 2012. Fuel cell electric vehicles and hydrogen infrastructure: status 2012. Energy Environ. Sci. 5, 8780–8798. doi:10.1039/C2EE22596D

Fuel Cell Today, 2012. History [WWW Document]. Johnson Matthey Plc. URL http://www.fuelcelltoday.com/history

FuelCells.org, 2012. Markets [WWW Document]. Fuel Cells 2000. URL http://www.fuelcells.org/base.cgim?template=markets

Honda Motor Company, 2015a. History FCX-V4 (2001) [WWW Document]. Honda Worldw. Site. URL http://world.honda.com/FuelCell/FCX/history/2001/

Honda Motor Company, 2015b. History FCX (2002) [WWW Document]. Honda Worldw. Site. URL http://world.honda.com/FuelCell/FCX/history/2002/

Honda Motor Company, 2015c. History New FXC (2003) [WWW Document]. Honda Worldw. Site. URL http://world.honda.com/FuelCell/FCX/history/2003/

Honda Motor Company, 2015d. History New FCX (2004) [WWW Document]. Honda Worldw. Site. URL http://world.honda.com/FuelCell/FCX/history/2004/

Honda Motor Company, 2008. Honda Announces First FCX Clarity Customers and World's First Fuel Cell Vehicle Dealership Network as Clarity Production Begins in Japan [WWW Document]. News Releases. URL http://world.honda.com/news/2008/4080616First-FCX-Clarity/index.html

Ishitani, H., 2010. The State of Our Efforts Toward General Adoption by 2015, and Future Issues, in: JHFC Seminar. JHFC.

Maeda, A., 2003. Innovation in Fuel Cell Technologies in Japan: Development and Commercialization of Polymer Electrolyte Fuel Cells.

Marscheider-Weidemann, F., Schirrmeister, E., Roser, A., 2009. Key role of fuel cells, in: Ball, M., Wietschel, M. (Eds.), The Hydrogen Economy: Opportunities and Challenges. Cambridge University Press, Cambridge, pp. 348–384.

Mytelka, L.K., Boyle, G., 2008. Making choices about hydrogen: transport issues for developing countries. United Nations University, New York.

Prater, K., 1990. The renaissance of the solid polymer fuel cell. J. Power Sources 29, 239–250. doi:http://dx.doi.org/10.1016/0378-7753(90)80023-7

Sandstede, G., Cairns, E.J., Bagotsky, V.S., Wiesener, K., 2010. History of low temperature fuel cells, in: Handbook of Fuel Cells. John Wiley & Sons, Ltd, pp. 145–218. doi:10.1002/9780470974001.f104011

Schaeffer, G.J., 1998. A history of fuel cells, in: Fuel Cells for the Future: A Contribution to Technology Forecasting from a Technology-Dynamics Perspective. Enschede, pp. 349–407.

Toyota Motors, 2004. Toyota FCHV (Fuel Cell Hybrid Vehicle) Book.

11.5. APPENDIX 5: EXAMPLE OF PROPOSED CODING SCHEME FOR FUTURE RESEARCH

Instance no: __

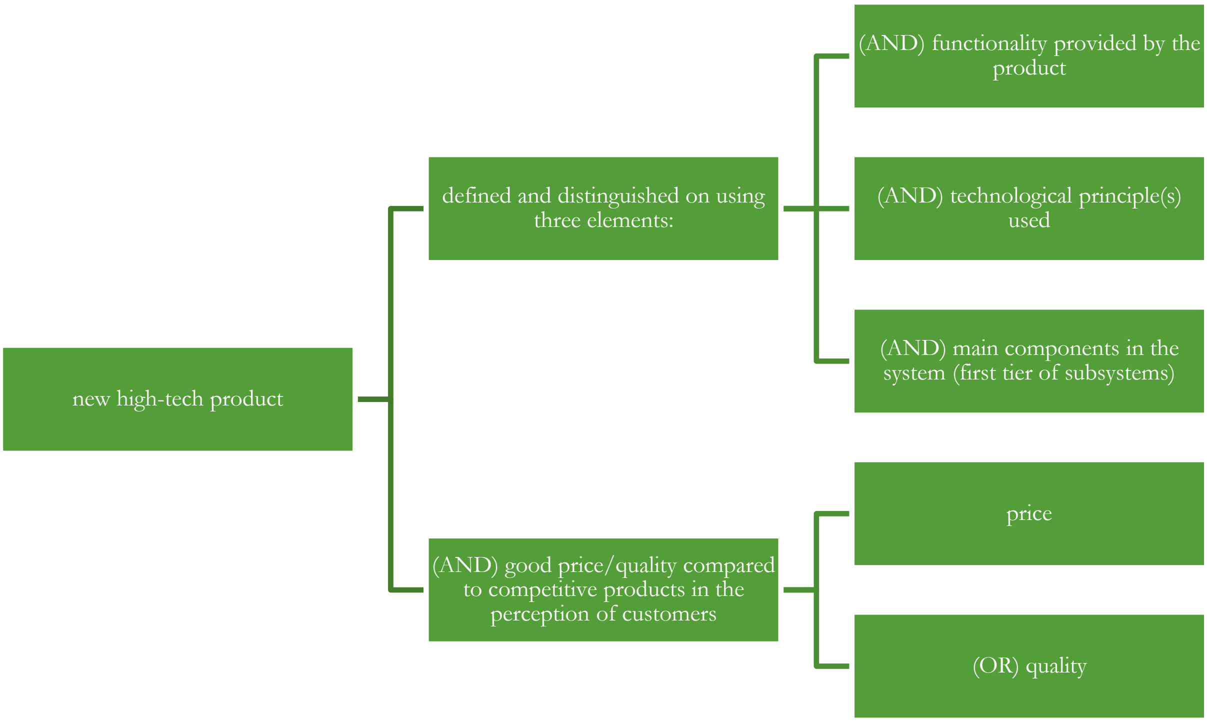
Technology: ____________________

Application: ____________________

Year of market introduction: _ _ _ _

11.5.1. NEW HIGH-TECH PRODUCT

The product can be defined and distinguished using three elements: the functionality provided by the product, the technological principle(s) used and the main components in the system (first tier of subsystems). The unavailability of (one or more components of) the product means that large-scale diffusion is not (yet) possible. The product needs to have a good price/quality compared to competitive products in the perception of customers before large-scale diffusion is possible.



1) Degree to which the functionality provided by the product can be defined and distinguished.

a) clearly defined and distinguished, stable over time b) some uncertainty regarding functionality c) alternative definitions of functionality (schools) d) uncertain: quick changes of functionality over time: unstable unit e) not enough information	Comments on the choice (optionally):

2) Degree to which the technological principle(s) used in the production of the product is(are) defined and distinguished.

a) Clearly defined and distinguished b) some uncertainty regarding the technological principle c) alternative definitions of the technological principle (schools)	Comments on the choice (optionally):

d) uncertain: quick changes of technological principle over time: unstable unit e) not enough information	

3) Degree to which the main components in the system (first tier of subsystems) can be defined and distinguished.

a) Clearly defined and distinguished b) some uncertainty regarding the main components c) alternative definitions of the main components (schools) d) uncertain: quick changes of main components over time: unstable unit e) not enough information	Comments on the choice (optionally):

4) The price of the product as compared to competitive products in the perception of customers:

a) Higher b) Somewhat higher c) Somewhat lower d) Low e) Not enough information	Comments on the choice (optionally):

5) The quality of the product as compared to competitive products in the perception of customers:

a) Higher b) Somewhat higher c) Somewhat lower d) Low e) Not enough information	Comments on the choice (optionally):

CONTEXTUAL FACTORS

If the core factor is found ABSENT, please skip this section and proceed to the next core factor. Note: ABSENT=((1) AND (2) AND (3)) AND ((4) OR (5)); PRESENT=NOT(ABSENT).

6) Degree to which the knowledge of the technology causes the presence of the core factor. The knowledge of the technology refers to the knowledge required to develop, produce, replicate and control the technological principles in a product.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	Comments on the choice (optionally):

7) Degree to which the knowledge of the application causes the presence of the core factor. Knowledge of the application can refer to knowing potential applications, such as the case when a technological principle is demonstrated but there is no clue about its practical application. A lack of knowledge of the application can also refer to customers that do not know how to use a new product in a particular application.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources)	Comments on the choice (optionally):

c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	

8) Degree to which the natural resources, labour and capital are the cause behind the core factor. Each of them can be required for the production system, for complementary products and services, or for the high-tech product itself. The lack of any of the three could block large-scale diffusion. Labour excludes the human capital that resides in the organization, and capital refers to substantial financial resources required in the aforementioned sense.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	Comments on the choice (optionally):

9) Degree to which the socio-cultural aspects are the cause behind the core factor. Socio-cultural aspects refer to the norms and values in a particular culture. These aspects might be less formalized than the laws and rules in the institutional aspects.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	Comments on the choice (optionally):

10) Degree to which the macro-economic aspects are the cause behind the core factor. Macro-economic aspects refer to the economic situation. For instance, a recession can stifle the diffusion of a new high-tech product.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	Comments on the choice (optionally):

11) Degree to which accidents or events are the cause behind the core factor. Accidents or events such as wars, accidents in production, accidents in the use of products can have a devastating effect on the diffusion of a new high-tech product.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	Comments on the choice (optionally):

12) Degree to which 'installed base' is the cause behind the core factor. The number of goods sold can influence the availability of the complementary products or services, in the presence of network externalities.

a) Explicitly the cause (sources agree on the explanation) b) Implicitly the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) c) Explicitly not the cause (sources agree on the lack of influence of this factor) d) Implicitly not the cause (sources would agree with the explanation; i.e. argumentation based on the data from sources) e) Not enough information	Comments on the choice (optionally):

11.5.2. PRODUCTION SYSTEM

Availability of a good production system is required for large-scale diffusion. In some cases a product can be created in small numbers as a kind of craftsmanship but industrial production technologies are not yet available. In that case large-scale diffusion is not possible.

13) Status of the production facilities currently in place.

a) There are readily-available production facilities b) The production facilities are already in construction and will soon be finished (one year at maximum) c) The production facilities can be built relatively quickly (order of years) d) The production facilities cannot be build or may take very long (order of decades) e) Not enough information	Comments on the choice (optionally):

14) Degree to which the production processes are controlled.

a) The products and their quality are (almost) identical between different batches b) There is some variance between different batches, but there's (little to) no impact on the final quality c) There is some variance between different batches, and the final quality cannot always be assured (up to σ% of the products are scrapped) d) There is large variance between different batches, and the final quality cannot be assured e) Not enough information	Comments on the choice (optionally):

15) Production capacity, defined as the number of products that may be produced using the available production assets.

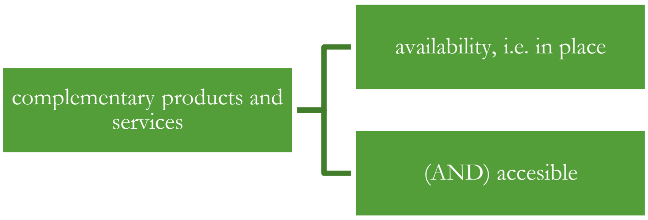
a) The product can be created in large numbers, with minor or no changes in the production assets (e.g. line re-organization, new dyes) b) The product can be created in large numbers, with significant changes in the production assets (e.g. capital investments in new production robots, co-creation of unique production robot) c) The product can be created in small numbers, using industrial equipment and limited manual labour (e.g. complex and/or time consuming CNC production of each product [component], time consuming 3D printing process) d) The product can be created in small numbers, as a kind of craftsmanship (e.g. shaping of metal sheets by hand) e) Not enough information	Comments on the choice (optionally):

CONTEXTUAL FACTORS

If the core factor is found ABSENT, please skip this section and proceed to the next core factor. Note: ABSENT=((12) AND (13) AND (14); PRESENT=NOT(ABSENT). Section identical to Contextual Factors, page 208; for brevity, not to be repeated.

11.5.3. COMPLEMENTARY PRODUCTS & SERVICES

Complementary products and services refer to products and services required for the production, distribution, adoption and use. The product together with complementary products and services forms a socio-technological system. The unavailability of elements in that system means that large-scale diffusion is not (yet) possible.



16) The degree to which the complementary products & services for the production of the product are in place.

a) There are readily-available complementary products & services b) The complementary products & services are soon to be in place (one year at maximum)	Comments on the choice (optionally):

c) The completion of complementary products & services can be done relatively quickly (order of years) d) The production facilities cannot be build or may take very long (order of decades) e) Not enough information	

17) The degree to which the complementary products & services are available to the actors involved in the production and/or supply of the products, or to the customers.

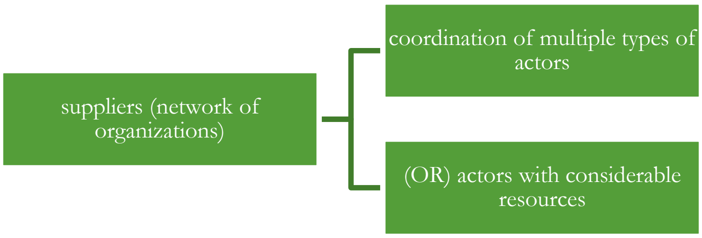
a) There are readily-accessible complementary products & services b) The complementary products & services are soon to be accessible (one year at maximum) c) The complementary products & services can become accessible relatively quickly (order of years) d) The complementary products & services cannot be made accessible or may take very long until they are made available (order of decades) e) Not enough information	Comments on the choice (optionally):

CONTEXTUAL FACTORS

If the core factor is found ABSENT, please skip this section and proceed to the next core factor. ABSENT=(22) AND (23);PRESENT=NOT(ABSENT). Section identical to Contextual Factors, page 208; for brevity, not to be repeated.

11.5.4. SUPPLIERS (NETWORK OF ORGANIZATIONS)

The producers and suppliers refer to the actors involved in the supply of the product. Sometimes multiple types of actors are required to supply the entire system. In that case a kind of coordination (network) is required. Sometimes actors with considerable resources are required, for example to provide an infrastructure. If one or more vital roles, resources or types of coordination are not present in the socio-technological system, large-scale diffusion is blocked.



18) Required level of the coordination of the network required in the supply of the product:

a) Very small (virtually market mechanisms alone are sufficient) b) Small (e.g. coordination of existing first tier suppliers of automotive firms; joint-ventures) c) Large (e.g. dispersed network) d) Very large (virtually no coordination possibilities) e) Not enough information	Comments on the choice (optionally):

19) Degree of required actors with considerable resources required in the supply of the product.

a) Very small (virtually no considerable resources required) b) Small (some resources are required, but the negotiation power of the actors owning the resources is not	Comments on the choice (optionally):

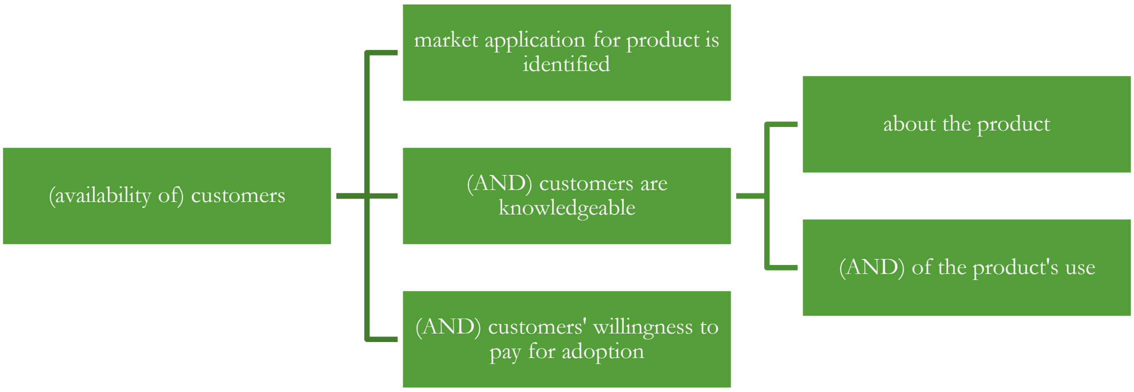
considerable) c) Large (considerable resources required or the negotiation power of the actors owning the resources is considerable) d) Very large (considerable resources required and the negotiation power of the actors owning the resources is considerable; e.g. complete new railway infrastructure in a region) e) Not enough information	

CONTEXTUAL FACTORS

If the core factor is found ABSENT, please skip this section and proceed to the next core factor. ABSENT=(29) OR (30);PRESENT=NOT(ABSENT). Section identical to Contextual Factors, page 208; for brevity, not to be repeated.

11.5.5. CUSTOMERS

The availability of customers means that a market application for the product is identified, that customer segments for these applications exist and that the customers are knowledgeable about the product and its use and are willing and able to pay for adoption. If applications are unknown or if customers groups do not exist, are not able to obtain the product or are unaware of the benefits of the product, large-scale diffusion is blocked.



20) Degree to which the market application for the product is identified.

a) clearly defined and distinguished b) some uncertainty regarding the market application c) alternative views on the market application d) uncertain: no convergence on the views towards functionality e) not enough information	Comments on the choice (optionally):

21) Degree to which customers are knowledgeable about the product.

a) Very knowledgeable (virtually no promotion required) b) Knowledgeable c) Barely knowledgeable d) Not knowledgeable at all (the product is completely unknown to consumers; e.g. skunk works) e) Not enough information	Comments on the choice (optionally):

22) Degree to which customers are knowledgeable about the product's use.

a) Very knowledgeable (virtually no manuals/instructions required) b) Knowledgeable	Comments on the choice (optionally):

c) Barely knowledgeable d) Not knowledgeable at all (the product's use is radically new to the market) e) Not enough information	

23) Estimated willingness to pay of customers for the adoption of the product.

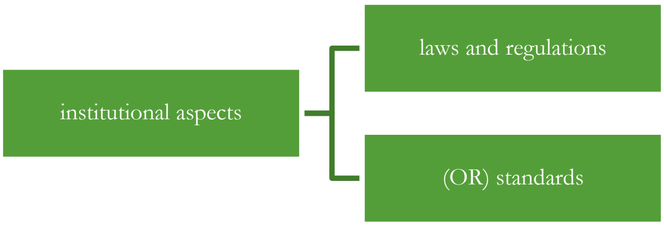
a) Very large (virtually zero price elasticity of demand) b) Large c) Small d) Very small (virtually no demand for any positive price range) e) Not enough information	Comments on the choice (optionally):

CONTEXTUAL FACTORS

If the core factor is found ABSENT, please skip this section and proceed to the next core factor. ABSENT=(37) AND ((38) AND (39)) AND (40);PRESENT=NOT(ABSENT).). Section identical to Contextual Factors, page 208; for brevity, not to be repeated.

11.5.6. INSTITUTIONAL ASPECTS (LAWS, RULES AND STANDARDS)

The regulatory and institutional environment refers to the laws and regulations that indicate how actors (on the supply and demand side of the market) deal with the socio-technological system. These laws and regulations can either stimulate the application of radically new high-tech products (such as subsidy that stimulates the use of sustainable energy) or completely block it (such as laws prohibiting something).



24) Degree to which (existing) laws and regulations stimulate or hinder the application of the product.

a) Very large (virtually the application is not permitted under the current institutional framework) b) Large c) Small d) Very small (virtually no influence) e) Not enough information	Comments on the choice (optionally):

25) Degree to which existing industry-standards stimulate or hinder the supply, production or adoption of the product.

a) Very large stimulus (virtually the application is compatible with current industry standards) b) Large stimulus c) Small hindering effect d) Very large hindering effect (virtually the application is not compatible with current industry standards) e) Not enough information	Comments on the choice (optionally):

CONTEXTUAL FACTORS

If the core factor is found ABSENT, please skip this section and proceed to the next core factor. ABSENT=(47) OR (48);PRESENT=NOT(ABSENT). Section identical to Contextual Factors, page 208; for brevity, not to be repeated.

11.5.7. NICHE STRATEGIES

For each market situation please repeat the coding procedure defined below; whereby market situation is defined as a pair of one core factor and the corresponding contextual factor (i.e. the cause):

26) Indicate in bold the corresponding market situation, respectively which of the following niche strategies was/were deliberately chosen by the (network of) organization(s) in that situation.

Indicate the core factor: F1. New high-tech product F2. Production system F3. Complementary products and services F4. Suppliers (network of organizations) F5. Customers F6. Institutional aspects (laws, rules and standards)	Indicate the contextual factor, i.e. the cause for the core factor: FF1. Knowledge of technology FF2. Knowledge of application FF3. Natural resources, labour and capital FF4. Socio-cultural aspects FF5. Macro-Economic aspects FF6. Accidents or events

Please indicate which of the following niche strategies was/were deliberately chosen by the (network of) organization(s) for the particular market situation indicated above, i.e. the pair of contextual and core factors.		
S1. Demo, experiment and develop niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S2. Top niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S3. Subsidized niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S4.i. Technological redesign niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S4.ii. Social redesign niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S5. Dedicated system or stand-alone niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):

S6. Hybridization or adaptor niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S7. Educate niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S8. Geographic niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S9. Lead user niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S10. Explore multiple markets niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):
S11. Leasing niche strategy	a) Explicitly deliberate b) Implicitly deliberate c) Explicitly not used d) Implicitly not used e) Not enough information	Comments on the choice (optionally):

BIBLIOGRAPHY

Adamson, K.A., 2003. An examination of consumer demand in the secondary niche market for fuel cell vehicles in Europe. *International Journal of Hydrogen Energy*, 28(7), pp.771–780. Available at: http://www.sciencedirect.com/science/article/pii/S036031990200246X.

Andropoulos, C., 2015. The PDK Transmission: How Porsche's quick-shifting PDK works. *Excellence*, (226). Available at: http://www.excellence-mag.com/issues/226/articles/the-pdk-transmission?page=1#.VTbABCGqqko [Accessed April 1, 2015].

Aspelund, A., Madsen, T.K. & Moen, Ø., 2007. A review of the foundation, international marketing strategies, and performance of international new ventures. *European Journal of Marketing*, 41(11/12), pp.1423–1448. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/03090560710821242.

AudiWorld, 2003. The Sporty Direct Shift Gearbox DSG. Available at: http://www.audiworld.com/news/03/082703/content.shtml [Accessed April 1, 2015].

Ball, M., Wietschel, M. & Seydel, P., 2009. Hydrogen today. In M. Ball & M. Wietschel, eds. *The Hydrogen Economy: Opportunities and Challenges*. Cambridge: Cambridge University Press, pp. 254–270.

Barbir, F., 2013. Fuel Cell Applications. In F. B. T.-P. E. M. F. C. (Second E. Barbir, ed. *PEM Fuel Cells*. Boston: Academic Press, pp. 373–434. Available at: http://www.sciencedirect.com/science/article/pii/B9780123877109000102.

Barwell, F.T., 1973. Control of Braking. In *Automation and Control in Transport*. Oxford, New York, Toronto, Sydney, Braunschweig: Pergamon Press, pp. 146–158. Available at: http://www.sciencedirect.com/science/article/pii/B9780080169620500197.

Beecham, M., 2005. European interest in dual-clutch technology shifts up a gear. *JustAuto*. Available at: http://www.just-auto.com/analysis/european-interest-in-dual-clutch-technology-shifts-up-a-gear_id86405.aspx [Accessed April 1, 2015].

Behling, N.H., 2013a. Chapter 2 - Fuel Cells and the Challenges Ahead. In N. H. Behling, ed. *Fuel Cells: Current Technology Challenges and Future Research Needs*. Elsevier, pp. 7–32.

Behling, N.H., 2013b. Chapter 7 - History of Proton Exchange Membrane Fuel Cells and Direct Methanol Fuel Cells. In N. H. B. T.-F. C. Behling, ed. *Fuel Cells: Current Technology Challenges and Future Research Needs*. Elsevier, pp. 423–600. Available at: http://www.sciencedirect.com/science/article/pii/B9780444563255000077.

Behme, B., 1970. Trailering with the New Cars. *Field & Stream*, 75(7), pp.112–115. Available at: https://books.google.nl/books?id=ip-lKPhGqowC&pg=PA113.

BioAge Group, 2014. SAE taskforce completes two technical standards on hydrogen refueling; harmonizing the global infrastructure. *Green Car Congress*. Available at: http://www.greencarcongress.com/2014/03/20140326-j2601.html.

Bonhof, K., 2011. Current Progress of Fuel Cell and Hydrogen Demonstrations in Germany. *JHFC Seminar*. Available at: http://www.jari.or.jp/portals/0/jhfc/data/seminor/fy2010/pdf/day2_E_04.pdf [Accessed August 1, 2015].

BorgWarner, 2014. History. Available at: https://www.borgwarner.com/en/Company/History/default.aspx [Accessed April 1, 2015].

California Energy Commission, 2014. California Investing Nearly $50 Million in Hydrogen Refueling Stations. *News Release*. Available at: http://www.energy.ca.gov/releases/2014_releases/2014-05-01_hydrogen_refueling_stations_funding_awards_nr.html.

Carlson, E.J. et al., 2005. *Cost Analysis of PEM Fuel Cell*, Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/tiax_fc_cost_analysis_2005.pdf [Accessed May 20, 2008].

Carter, D., 2013. *The Cost of Platinum in Fuel Cell Electric Vehicles*,

Commercial Motor, 1968. Cheaper and better Maxaret. *Commercial Motor*, p.52. Available at: http://commercial-motor.archive.netcopy.co.uk/article/27th-september-1968/52/cheaper-and-better-maxaret.

Commercial Motor, 1969. Electronic Maxaret in production. *Commercial Motor*, p.42. Available at: http://archive.commercialmotor.com/page/31st-october-1969/42.

Commercial Motor, 1966a. Maxaret-Controlled Artic. *Commercial Motor*, (16th of September), p.100. Available at: http://commercial-motor.archive.netcopy.co.uk/article/16th-september-1966/100/maxaret [Accessed June 1, 2015].

Commercial Motor, 1966b. Shell's first Maxaret-equipped tanker demonstrated. *Commercial Motor*, p.41. Available at: http://commercial-motor.archive.netcopy.co.uk/article/28th-october-1966/41/shells-first-maxaret-equipped-tanker-demonstrated.

Crane Aerospace & Electronics, 2015. Military Aircraft Brake Control Systems. Available at: http://www.craneae.com/Products/Landing/BrakeControlMilitary.aspx [Accessed June 1, 2015].

Curtin, S. & Gangi, J., 2013. *2013 Fuel Cell Technologies Market Report*, Washington, D.C. Available at: http://energy.gov/sites/prod/files/2014/11/f19/fcto_2013_market_report.pdf.

Curtis, A., 1971. Taking the skid out of braking. *New Scientist*, 51(764), pp.358–361. Available at: https://books.google.nl/books?id=fqkkbpoFA5oC&pg=PA359 [Accessed May 20, 2005].

Cutter, C., 1968. Coming Soon! "Skidproof" Cars. *Popular Mechanics*, 129(2), pp.104–106, 206. Available at: https://books.google.nl/books?id=jdQDAAAAMBAJ.

Daimler Communications, 2008. Mercedes-Benz and the invention of the anti-lock braking system: ABS, ready for production in 1978. Available at: http://media.daimler.com/dcmedia/0-921-657486-1-803841-1-0-0-0-0-1-11701-614318-0-1-0-0-0-0-0.html.

Day, A., 2014. Electronic Braking Systems. In A. Day, ed. *Braking of Road Vehicles*. Oxford: Butterworth-Heinemann, pp. 385–428.

DeBresson, C., 1995. Predicting the most likely diffusion sequence of a new technology through the economy: The case of superconductivity. *Research Policy*, 24(5), pp.685–705. Available at: http://www.sciencedirect.com/science/article/pii/0048733394007915.

Debruyne, M. et al., 2002. The impact of new product launch strategies on competitive reaction in industrial markets. *Journal of Product Innovation Management*, 19(2), pp.159–170. Available at: http://dx.doi.org/10.1111/1540-5885.1920159.

Dell, R.M., Moseley, P.T. & Rand, D.A.J., 2014. Hydrogen, Fuel Cells and Fuel Cell Vehicles. In R. M. Dell, P. T. Moseley, & D. A. J. Rand, eds. *Towards Sustainable Road Transport*. Boston: Academic Press, pp. 260–295. Available at: http://www.sciencedirect.com/science/article/pii/B9780124046160000086.

Dinis, A., 2006. Marketing and innovation: Useful tools for competitiveness in rural and peripheral areas. *European Planning Studies*, 14(1), pp.9–22. Available at: http://dx.doi.org/10.1080/09654310500339083.

Dziura, M.J., 2001. Innovation: sources and strategies. *International Journal of Technology Management*, 21(5), pp.612–627. Available at: http://inderscience.metapress.com/content/7FX29306DJE8NA0G.

Eberle, U., Muller, B. & von Helmolt, R., 2012. Fuel cell electric vehicles and hydrogen infrastructure: status 2012. *Energy & Environmental Science*, 5(10), pp.8780–8798. Available at: http://dx.doi.org/10.1039/C2EE22596D.

Fisher, E. & Schuurbiers, D., 2013. Socio-technical Integration Research: Collaborative Inquiry at the Midstream of Research and Development. In N. Doorn et al., eds. *Early engagement and new technologies: Opening up the laboratory SE - 5*. Philosophy of Engineering and Technology. Springer Netherlands, pp. 97–110. Available at: http://dx.doi.org/10.1007/978-94-007-7844-3_5.

Fuel Cell Today, 2012a. DMFC. *Johnson Matthey Plc*. Available at: http://www.fuelcelltoday.com/technologies/dmfc [Accessed June 1, 2015].

Fuel Cell Today, 2012b. History. *Johnson Matthey Plc*. Available at: http://www.fuelcelltoday.com/history.

Fuel Cell Today, 2012c. PEMFC. *Johnson Matthey Plc*. Available at: http://www.fuelcelltoday.com/technologies/pemfc [Accessed June 1, 2015].

Fuel Cell Today, 2012d. Technologies. *Johnson Matthey Plc*. Available at: http://www.fuelcelltoday.com/technologies [Accessed June 1, 2015].

FuelCells.org, 2015. Charts. *Fuel Cells 2000*. Available at: http://www.fuelcells.org/base.cgim?template=charts.

FuelCells.org, 2012. Markets. *Fuel Cells 2000*. Available at: http://www.fuelcells.org/base.cgim?template=markets.

Goetz, M., Levesley, M.C. & Crolla, D.A., 2005. Dynamics and control of gearshifts on twin-clutch transmissions. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* , 219 (8), pp.951–963. Available at: http://pid.sagepub.com/content/219/8/951.abstract.

Google Guide, 2012a. Interpreting Your Query. *Part I: Query Input*, 2015(/04/2015). Available at: http://www.googleguide.com/interpreting_queries.html#stemming.

Google Guide, 2012b. Special Characters: Summary. *Part I: Query Input*, 2015(/04/2015). Available at: http://www.googleguide.com/basic_operator_summary.html.

Hagen, B. et al., 2012. International strategy and performance—Clustering strategic types of SMEs. *International Business Review*, 21(3), pp.369–382. Available at: http://www.sciencedirect.com/science/article/pii/S0969593111000503.

Honda Motor Company, 2015a. History FCX (2002). *Honda Worldwide Site*. Available at: http://world.honda.com/FuelCell/FCX/history/2002/.

Honda Motor Company, 2015b. History FCX-V4 (2001). *Honda Worldwide Site*. Available at: http://world.honda.com/FuelCell/FCX/history/2001/.

Honda Motor Company, 2015c. History New FXC (2003). *Honda Worldwide Site*. Available at: http://world.honda.com/FuelCell/FCX/history/2003/.

Honda Motor Company, 2008a. Honda Announces First FCX Clarity Customers and World's First Fuel Cell Vehicle Dealership Network as Clarity Production Begins in Japan. *News Releases*. Available at: http://world.honda.com/news/2008/4080616First-FCX-Clarity/index.html.

Honda Motor Company, 2008b. Honda Unveils Japan Model of FCX Clarity Fuel Cell Vehicle - Leasing in Japan to begin November 2008. *News Releases*. Available at: http://world.honda.com/news/2008/4080702FCX-Clarity/index.html.

Hoogma, R., 2000. Exploiting technological niches; strategies for experimental introduction of electric vehicles. In *Mumford reeks 5*. Enschede: Twente University Press.

HyNor, 2011. About HyNor. Available at: http://hynor.no/en/about-hynor [Accessed August 1, 2015].

Hyundai Motor America, 2015. Tucson Fuel Cell. Available at: https://www.hyundaiusa.com/tucsonfuelcell/.

Iansiti, M. & Levien, R., 2002. Niche strategies. In *The New Operational Dynamics of Business Ecosystems: Implications for Policy, Operations and Technology Strategy*. Citeseer, pp. 47–54.

Iansiti, M. & Levien, R., 2004. Strategy as Ecology. *Harvard Business Review*, 82(3), pp.68–81.

Ishitani, H., 2010. The State of Our Efforts Toward General Adoption by 2015, and Future Issues. In *JHFC Seminar*. JHFC.

Jaynes, N., 2014. How the tech from the crazy cars of Le Mans will make it to your garage. *Digital Trends*. Available at: http://www.digitaltrends.com/cars/le-mans-tech/.

JHFC, 2011a. About JHFC Project. Available at: http://www.jari.or.jp/portals/0/jhfc/e/jhfc/index.html.

JHFC, 2011b. Event History. Available at: http://www.jari.or.jp/portals/0/jhfc/e/news/event/index.html.

Joel, S., 1996. Antilock Brake System. *How Products Are Made*. Available at: http://www.encyclopedia.com/doc/1G2-2896600014.html [Accessed May 1, 2015].

Kacher, G., 2010. 2011 Man of the Year: Ferdinand Piech. *Automobile Magazine*. Available at: http://www.automobilemag.com/features/awards/1101_2011_man_of_the_year_ferdinand_piech/ [Accessed July 1, 2015].

Katz, M.L. & Shapiro, C., 1985. Network Externalities, Competition, and Compatibility. *The American Economic Review*, 75(3), pp.424–440 CR – Copyright © 1985 American Econo. Available at: http://www.jstor.org/stable/1814809.

Katz, M.L. & Shapiro, C., 1986. Technology Adoption in the Presence of Network Externalities. *Journal of Political Economy*, 94(4), pp.822–841. Available at: http://www.jstor.org/stable/1833204.

Kegresse, A., 1939. Hydraulic change gear device for automobile vehicles. Available at: https://www.google.nl/patents/US2163202.

Kemp, R., Schot, J. & Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis and Strategic Management*, 10(2), pp.175–195. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-0001513530&partnerID=40&md5=f2cacc6f527b108ade80da4c92f515a1.

Kiley, D., 2015. How Ferdinand Piech Lost Control of Volkswagen. *Automobile Magazine*. Available at: http://www.automobilemag.com/features/columns/1504-how-ferdinand-piech-lost-control-of-volkswagen/ [Accessed July 1, 2015].

Koscs, J., 2013. Anti-Lock Brakes: Who Was Really First? *Hagerty*. Available at: https://www.hagerty.com/articles-videos/Articles/2013/04/09/Antilock-Brakes.

Kotler, P., 2000. Winning Markets Through Strategic Planning Implementation, and Control. In *Marketing Management: Millennium Edition*. Prentice Hall, pp. 39–62. Available at: http://books.google.nl/books?id=i-kIPwAACAAJ.

Kuhlgatz, D., 2014. *Bosch Automotive: Supplement 2 of Bosch History Journal*, Available at: http://www.bosch.com/content2/publication_forms/en/downloads/Sonderheft_2_automotive_en.pdf.

Kyodo, 2014. Toyota to supply fuel cell vehicle parts to other automakers. *The Japan Times*. Available at: http://www.japantimes.co.jp/news/2014/07/03/business/corporate-business/toyota-supply-fuel-cell-vehicle-parts-automakers [Accessed May 20, 2007].

Van der Laak, W.W.M., Raven, R.P.J.M. & Verbong, G.P.J., 2007. Strategic niche management for biofuels: Analysing past experiments for developing new biofuel policies. *Energy Policy*, 35(6), pp.3213–3225. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-33947721976&partnerID=40&md5=39219b0736360f5927befa8f5811b30a.

Lawes, J., 2014. Anti-lock Braking Systems. In *Car Brakes: A Guide to Upgrading, Repair and Maintenance*. Crowood. Available at: https://books.google.nl/books?id=Sod8AwAAQBAJ.

Levine, J., 2014. Anti-lock braking system - Early systems. In *Royal Enfield 70 Success Secrets - 70 Most Asked Questions On Royal Enfield - What You Need To Know*. Emereo Publishing. Available at: https://books.google.nl/books?id=rwYQBwAAQBAJ.

Levinthal, D.A., 1998. The Slow Pace of Rapid Technological Change: Gradualism and Punctuation in Technological Change. *Industrial and Corporate Change*, 7(2), pp.217–247. Available at: http://icc.oxfordjournals.org/content/7/2/217.abstract.

Lewin, T. ed., 2006. Bugatti Veyron Special. *Ricardo Quarterly Review, Q2*, pp.8–15. Available at: http://www.ricardo.com/Documents/RQ pdf/RQ 2006/RQ-Q2-2006.pdf.

Ludvigsen, E. ed., 2005. 969: The Turbo That Never Was. *Excellence*, (138), pp.111–116. Available at: http://www.flachbau.com/Documents-Media/965_Master.pdf [Accessed May 20, 2004].

Lumpkin, G.T. & Dess, G.G., 1996. Clarifying the Entrepreneurial Orientation Construct and Linking It to Performance. *The Academy of Management Review*, 21(1), pp.135–172. Available at: http://www.jstor.org/stable/258632.

Lynn, G.S., Morone, J.G. & Paulson, A.S., 1996. Marketing and discontinuous innovation: The probe and learn process. *California Management Review*, (3), pp.8–37. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-0030528170&partnerID=40&md5=c11cd8080894e934e5dd9db20afe89c8.

Maeda, A., 2003. *Innovation in Fuel Cell Technologies in Japan: Development and Commercialization of Polymer Electrolyte Fuel Cells*, Available at: http://www.oecd.org/innovation/inno/31968247.pdf.

March, J.G., 1991. Exploration and Exploitation in Organizational Learning. *Organization Science*, 2(1), pp.71–87. Available at: http://www.jstor.org/stable/2634940.

Marscheider-Weidemann, F., Schirrmeister, E. & Roser, A., 2009. Key role of fuel cells. In M. Ball & M. Wietschel, eds. *The Hydrogen Economy: Opportunities and Challenges*. Cambridge: Cambridge University Press, pp. 348–384.

Mintzberg, H., Ahlstrand, B.W. & Lampel, J., 1998. *Strategy Safari: The Complete Guide Through the Wilds of Strategic Management* 1st ed., The Free Press.

Mintzberg, H. & Waters, J.A., 1985. Of strategies, deliberate and emergent. *Strategic Management Journal*, 6(3), pp.257–272. Available at: http://dx.doi.org/10.1002/smj.4250060306.

Moore, G.A., 1991. *Marketing high-tech products*, United States: Harper Business Essentials.

Naunheimer, H. et al., 2011. *Automotive transmissions: Fundamentals, Selection, Design, and Application* 2nd ed., Heidelberg Dordrecht London New York: Springer.

Naval Technology, 2011. Full steam ahead for submarine propulsion. Available at: http://www.naval-technology.com/features/feature127881/ [Accessed May 20, 2007].

Nunney, M.J., 1992. Anti-lock brakes and traction control. In *Light and Heavy Vehicle Technology*. Newnes, pp. 572–580. Available at: http://www.sciencedirect.com/science/article/pii/B9780750604772500340.

Olivi, D., 2013. *Development of control-oriented models of Dual Clutch Transmission systems*. University of Bologna. Available at: http://amsdottorato.unibo.it/5683/1/Olivi_Davide_tesi.pdf.

Ortt, J.R., 2012. Market creation for radically new technologies: A literature review on the role of market niches. In *2012 18th International Conference on Engineering, Technology and Innovation, ICE 2012 - Conference Proceedings*. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84867911406&partnerID=40&md5=a5c5bc08e3008d66b0916845abeaeafb.

Ortt, J.R. & Dedehayir, O., 2010. Factors hampering technology system progress during the life cycle: What are these factors and how to deal with them? In Y. Hosni, ed. *Proceedings of 19th International Conference on Management of Technology, IAMOT 2010*. Cairo, Egypt.

Ortt, J.R. & Delgoshaie, N., 2008. Why does it take so long before the diffusion of new high-tech products takes off? In B. Abu-Hijleh et al., eds. *Creating & Managing a Knowledge Economy*. Dubai: The British Economy in Dubai, pp. 2–15.

Ortt, J.R., Langley, D.J. & Pals, N., 2013. Ten Niche Strategies To Commercialize New High-Tech Products. *2013 IEEE International Technology Management Conference & 19th ICE Conference*, p.24.

Ortt, J.R. & Schoormans, J.P.L., 2004. The pattern of development and diffusion of breakthrough communication technologies. *European Journal of Innovation Management*, 7(4), pp.292–302. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/14601060410565047.

Ortt, J.R., Shah, C.M. & Zegveld, M.A., 2007. Strategies to Commercialise Breakthrough Technologies. In *International Association for Management of Technology*.

Ortt, J.R. & Suprapto, M., 2011. The role of strategic niches in creating large-scale applications for high-tech products. In Y. Hosni, ed. *IAMOT2011*. p. 24.

Ortt, J.R., Trevino Barbosa, S.I. & Meijer, S.A., 2012. Sequences of Niche Applications Prior to Large Scale Diffusion. In Y. Hosni, S. C. Hung, & T. Khalil, eds. *Managing Technology-Service Convergences in the Post-Industrialized Society*. Hsinchu, Taiwan: IAMOT2012, pp. 1–12.

Parrish, E.D., Cassill, N.L. & Oxenham, W., 2006a. Niche market strategy for a mature marketplace. *Marketing Intelligence & Planning*, 24(7), pp.694–707. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/02634500610711860.

Parrish, E.D., Cassill, N.L. & Oxenham, W., 2006b. Niche market strategy in the textile and apparel industry. *Journal of Fashion Marketing and Management: An International Journal*, 10(4), pp.420–432. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/13612020610701956.

Pleitgen, F., 2011. Super-stealth sub powered by fuel cell. Available at: http://edition.cnn.com/2011/TECH/innovation/02/22/hybrid.submarine/index.html?_s=PM:TECH.

Porter, M.E., 1998a. Competitive Strategy: The Core Concepts. In *Competitive Advantage: Creating and Sustaining Superior Performance*. New York: Free Press, pp. 1–30.

Porter, M.E., 1998b. Generic Competitive Strategies; A Framework for Competitor Analysis; In *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. New York: Free Press, pp. 34–74.

Porter, M.E., 1980. Introduction. In *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. New York: Free Press, pp. 1–28.

Porter, M.E., 1996. What Is Strategy? *Harvard Business Review*, 74(6), pp.61–78.

Prater, K., 1990. The renaissance of the solid polymer fuel cell. *Journal of Power Sources*, 29(1–2), pp.239–250. Available at: http://www.sciencedirect.com/science/article/pii/0378775390800237.

Ramsden, J.M. et al. eds., 1975. Dunlop Aviation is 50. *Flight International*, (3448), pp.607–608. Available at: http://www.flightglobal.com/pdfarchive/view/1975/1975 - 0681.html [Accessed May 1, 2015].

Reynolds, J., 1990. *Best of British bikes*, Patrick Stephens. Available at: https://books.google.nl/books?id=X9Xb0YOEXOEC.

Rhee, M., Kim, Y.C. & Han, J., 2006. Confidence in imitation: Niche-width strategy in the UK automobile industry. *Management Science*, 52(4), pp.501–513.

Richardson, C., 2003. Inspiration for Audi's new Direct Shift Gearbox came from the double-clutch PDK box developed in Waiter Rohrl's awesome Evolution 2 quattro. *The Audi Magazine*, (Winter). Available at: http://www.urquattro.fr/Web/Pages/Journaux/diversetrangers/JE08.html [Accessed April 1, 2015].

Road Test, 1971. Computerized Braking. *Road Test*, (September), pp.38–43. Available at: http://imperialclub.com/Articles/71RoadTest/index.htm [Accessed May 1, 2015].

Robert Bosch GmbH, 2003a. 25th Bosch ABS anniversary. Available at: http://www.bosch.com/assets/en/company/innovation/theme03.htm.

Robert Bosch GmbH, 2003b. Bosch History. *Bosch History Magazine*, pp.1–35. Available at: http://www.docstoc.com/docs/91217236/.

Rogers, E.M., 2003. *Diffusion of Innovations*, New York: The Free Press.

Russ, C., 2008. Porsche's PDK: A quick look at the history and technology behind Porsche's new double-clutch gearbox. *CNET*. Available at: http://www.cnet.com/news/porsches-pdk/ [Accessed May 20, 2015].

Sandstede, G. et al., 2010. History of low temperature fuel cells. In *Handbook of Fuel Cells*. John Wiley & Sons, Ltd, pp. 145–218. Available at: http://dx.doi.org/10.1002/9780470974001.f104011.

Scandinavian Hydrogen Highway Partnership, 2015. Hydrogen for transport in the Scandinavian region. Available at: http://www.scandinavianhydrogen.org/about-shhp [Accessed May 20, 2008].

Schaeffer, G.J., 1998. A history of fuel cells. In *Fuel Cells for the Future: A contribution to technology forecasting from a technology-dynamics perspective*. Enschede, pp. 349–407. Available at: http://doc.utwente.nl/33778/.

Schaltegger, S., 2002. A framework for ecopreneurship. *Greener Management International*, 2002(38), pp.45–58.

Schot, J. & Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management*, 20(5), pp.537–554. Available at: http://dx.doi.org/10.1080/09537320802292651.

Scoltock, J., 2012. Adolphe Kégresse developed the dual-clutch transmission. *Automotive Engineer*. Available at: http://ae-plus.com/milestones/adolphe-kgresse-developed-the-dual-clutch-transmission [Accessed April 1, 2015].

Senatore, A., 2009. Advances in the Automotive Systems: An Overview of Dual-Clutch Transmissions. *Recent Patents on Mechanical Engineering*, 2(2), pp.93–101.

Severson, A., 2009. Mark of Success: The Lincoln Continental Mark Series. *Ate Up with Motor - Portraits of Automobile History*. Available at: http://ateupwithmotor.com/model-histories/lincoln-continental-mark-iii-iv-v/.

Sherman, D., 2012. A Tale of Two Porsche Seven-Speeds: Manual and PDK. *Car and Driver*. Available at: http://www.caranddriver.com/features/a-tale-of-two-porsche-seven-speeds-manual-and-pdk-tech-dept [Accessed July 1, 2015].

Shum, K.L. & Watanabe, C., 2007. Photovoltaic deployment strategy in Japan and the USA—an institutional appraisal. *Energy Policy*, 35(2), pp.1186–1195. Available at: http://www.sciencedirect.com/science/article/pii/S0301421506000991.

Smith, M.A. et al. eds., 1967. Special feature: Paris Show Guide. *Flight International*, (3037), p.847. Available at: http://www.flightglobal.com/pdfarchive/view/1967/1967 - 0869.html [Accessed May 1, 2015].

Smith, M.A. & King, H.F. eds., 1951. Civil Aviation News... *Flight and Aircraft Engineer*, LIX(2198), p.296. Available at: http://www.flightglobal.com/pdfarchive/view/1951/1951 - 0474.html [Accessed May 20, 2015].

Smith, M.A. & King, H.F. eds., 1953. Parisian Round-Up... *Flight and Aircraft Engineer*, LXIV(2321), p.83. Available at: http://www.flightglobal.com/pdfarchive/view/1953/1953 - 0915.html [Accessed May 1, 2015].

Solberg, C.A. & Durrieu, F., 2008. Strategy development in international markets: a two tier approach. *International Marketing Review*, 25(5), pp.520–543. Available at: http://www.emeraldinsight.com/doi/abs/10.1108/02651330810904071.

Starks, H.J.H., 1968. *Physics and road safety - Braking and stability of vehicles*, Crowthorne. Available at: ftp://ftp.iop.org/pub/physbull/physbull_19_1_january1968.pdf.

Stefanini, S., 2003. Shift in power to the gearbox. *Automotive Manufacturing Solutions*, pp.70–73. Available at: http://www.unofficialbmw.com/images/SHIFT1.pdf.

Stoklosa, A., 2013. Shift This: A History of Porsche's Sportomatic, Tiptronic, and PDK Transmissions. *Car and Driver*. Available at: http://blog.caranddriver.com/shift-this-a-history-of-porsches-sportomatic-tiptronic-and-pdk-transmissions/ [Accessed April 1, 2015].

Sutton, M., 2007. BorgWarner Refining Dual-Clutch Technology for New Applications. *WardsAuto*. Available at: http://wardsauto.com/ar/borgwarner_refining_technology [Accessed April 1, 2015].

Thompson, J.L., 1993. Chapter 1. In *Strategic Management: Awareness and Change*. London: Chapman & Hall.

Tisdell, C. & Seidl, I., 2004. Niches and economic competition: implications for economic efficiency, growth and diversity. *Structural Change and Economic Dynamics*, 15(2), pp.119–135. Available at: http://www.sciencedirect.com/science/article/pii/S0954349X0300002X.

Toyota Motor, 2005. TOYOTA FCHV Acquires Vehicle Type Certification. *News Release*. Available at: http://www.toyota.co.jp/en/news/05/0617.html.

Toyota Motor Sales USA, 2015. Mirai - Fuel Cell Vehicle. Available at: http://www.toyota.com/mirai/fcv.html.

Toyota Motors, 2004. *Toyota FCHV (Fuel Cell Hybrid Vehicle) Book*, Available at: http://www.toyotaaruba.com/readBlob.do?id=134 [Accessed June 1, 2015].

Trevino Barbosa, S.I., Ortt, J.R. & Meijer, S.A., 2011. *Commercialization of High-Tech Products: Niche Market Applications Prior to Large-Scale Diffusion*. Delft: Delft University of Technology. Available at: http://repository.tudelft.nl/view/ir/uuid:d494a760-da2a-4fe6-9218-10ef6aba2c52/.

Veloso, F. & Fixson, S., 2001. Make–Buy Decisions in the Auto Industry: New Perspectives on the Role of the Supplier as an Innovator. *Technological Forecasting and Social Change*, 67(2–3), pp.239–257. Available at: http://www.sciencedirect.com/science/article/pii/S0040162500000925.

Visnic, B., 2000. Tech & Trends. *WardsAuto*. Available at: http://wardsauto.com/news-amp-analysis/tech-trends-2.

Volkswagen AG, 2004. *Annual Report 2003*, Wolfsburg, Germany. Available at: http://www.volkswagenag.com/content/vwcorp/info_center/en/publications/2004/03/annual_report_2003.bin.html/binarystorageitem/file/20040309_gb2003_e.pdf.

Volkswagen AG, 2005a. *Annual Report 2004*, Wolfsburg, Germany. Available at: http://www.volkswagenag.com/content/vwcorp/info_center/en/publications/2005/03/annual_report_2004.bin.html/binarystorageitem/file/Gbericht_2004_en.pdf.

Volkswagen AG, 2007. *Annual Report 2006*, Wolfsburg, Germany. Available at: http://www.volkswagenag.com/content/vwcorp/info_center/en/publications/2007/03/Geschaeftsbericht_2006.bin.html/binarystorageitem/file/Annual_Report_2006_e.pdf.

Volkswagen AG, 2005b. *Double benefit: TDI engine plus DSG gearbox*, Wolfsburg, Germany. Available at: https://www.volkswagen-media-services.com/en/detailpage/-/detail/Double-benefit-TDI-engine-plus-DSG-gearbox/view/90028/6e1e015af7bda8f2a4b42b43d2dcc9b5?p_p_auth=oGysM013 [Accessed July 1, 2015].

Volkswagen AG, 2005c. *New interest in automatic gearboxes thanks to DSG®*, Wolfsburg, Germany. Available at: https://www.volkswagen-media-services.com/en/detailpage/-/detail/New-interest-in-automatic-gearboxes-thanks-to-DSG/view/90128/5ea8784c3b654f0aef71f2c5bf76826f?p_p_auth=oGysM013 [Accessed July 1, 2015].

Volkswagen AG, 2002. *Volkswagen DSG – Weltweit erstes Getriebe mit Doppelkupplung im Serien-Pkw (World's first double-clutch transmission in the production car)*, Wolfsburg, Germany. Available at: https://www.volkswagen-media-services.com/en/detailpage/-/detail/Volkswagen-DSG--Weltweit-erstes-Getriebe-mit-Doppelkupplung-im-

Serien-Pkw/view/86958/75d9972d9e87d3cfb605c0b3c81d8cc2?p_p_auth=mEGzb3FJ [Accessed July 1, 2015].

Volkswagen AG, 2009. *Volkswagen Supervisory Board approves Comprehensive Agreement for an Integrated Automotive Group with Porsche*, Wolfsburg, Germany. Available at: http://www.volkswagenag.com/content/vwcorp/info_center/en/news/2009/08/Volkswagen_Aufsichtsrat_stimmt_Grundlagenvereinbarung_fuer.html [Accessed May 20, 2015].

Weber, M. et al., 1999. *Experimenting with sustainable transport innovations: a workbook for strategic niche management*, Seville/Enschede: Universiteit Twente.

Wernle, B., 2005. Ford joins the shift to dual-clutch gearboxes. VW already uses the fuel-saving technology in numerous models. *Automotive News Europe*. Available at: http://europe.autonews.com/article/20050905/ANE/509050838/ford-joins-the-shift-to-dual-clutch-gearboxes [Accessed May 20, 2005].

Xiong, B., 2013. Governor Brown Signs AB 8. *California Fuel Cell Partnership*. Available at: http://cafcp.org/getinvolved/stayconnected/blog/governor_brown_signs_ab_8.

Yin, R.K., 2003. *Case Study Research: Design and Methods* 3rd ed., Thousand Oaks, CA: Sage Publications.

End.