The exploration of the reverse salient of electric vehicle systems for urban mobility

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Summary

Electrification transportation for urban mobility is a hot topic around the world. Many types of electric vehicles could be employed for urban mobility, but both the EVs' adoption rate and the deployment of their dependent infrastructures are either in the nascent stage or have not been commercialized. No study has studied the drawbacks of EV systems for urban areas in order to improve their performance. A methodology is needed to indicate the reverse salient, which represents the technical drawbacks and social barriers within a large scale technological system, that are hindering the EV diffusion. This paper employed morphological analysis to thoroughly explore all possible designs of electric vehicle systems for urban mobility. Based on the 45 explored electric vehicle configurations, the RS for each type of EV system are identified by consulting four automotive industry experts. The results are validated by confronting with the results from reviewing 34 previous literatures. Multiple technical and social RS are indicated with suggested strategies to overcome the RS. At last, the RS of China's EV market are analyzed and identified as government policies, consumer cultures and product diversity and market positioning. Multiple policy suggestions are given to the central government of China. Future studies can focus on analyzing RS for longer range applications; customer psychology and behavior towards EV; customer classifications for difference types of EVs; and analysis of policy incentives for EV adoption and charging behaviors.

Key words: reverse salient, battery electric vehicle, hybrid electric vehicle, fuel cell vehicle, infrastructure of electric vehicle, morphological analysis

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1 Introduction

During the past half century, sustainable mobility has been a hot topic globally among governments, environmental organizations, automobile companies and customers. The concept of “sustainable mobility” is similar as “sustainable transport/ vehicle”, which is focused on physical requirements of transport means, the infrastructures and transportation systems, but with border societal patterns and volumes of movement (Høyer, 2008). This project will not only focus on the physical artifacts of vehicles, but also analyze the social factors which influence the development of the vehicle system; hence “sustainable mobility” is used rather than “sustainable vehicles” in this paper. Electric vehicles (EVs), which fully or partially use electricity as propulsion power and electric motor to generate power for wheels, are seemed as good solutions to achieve the sustainable goal, since electricity could be generated from various renewable energy sources, such as wind power, solar power and nuclear power, etc., which not only largely decreases the greenhouse gas (GHG) emissions to the environment, but also reduces the dependence on petroleum of vehicles.

Generally, EVs can be classified into three categories: battery electric vehicle (BEV), hybrid electric vehicle (HEV) and fuel cell electric vehicle (FCEV). BEVs solely depend on electrochemical battery and electric motor to power the wheels, which can achieve zero direct CO_2 emission but with a relatively high up-front cost of the battery and short driving range problems due to insufficient charging infrastructures and battery capacity. HEVs combine both battery and combustion engine in the vehicle which largely extend the driving range of BEVs but cannot solve the pollution problem exhaustively. There are different types of HEVs according to the energy storage system being used to directly power the wheels, in which, plug-in HEV (PHEV) allows the vehicle to recharge the battery on the grid directly. FCEV is another type of EV which uses the fuel cell as primary energy storage system. Fuel cell is a form of battery that transfers chemical energy into electric energy via a reverse reaction of electrolysis of water with oxygen or other oxygen agents. Multiple types of EVs are available now in the market, while the FCEVs are still in the pilot phase, but they have been seemed as a promising technology for the future vehicles by many.

EVs are more environmental friendly than internal combustion vehicles (ICVs), because EVs can produce less direct CO_2 emission than ICVs. As shown in figure 1(a) (O’Keefe et al., 2011), if we use renewable resources for the electricity generation, BEVs show the lowest well to wheel GHG emission; although PHEVs partially use ICEs, the total GHG emission is still 27 tons smaller than ICVs. Although there are so many advantages of EVs, consumers are prohibitive to buy EVs because of the high upfront cost induced by the battery, short driving range and lack of infrastructures disadvantages, compare to ICVs.

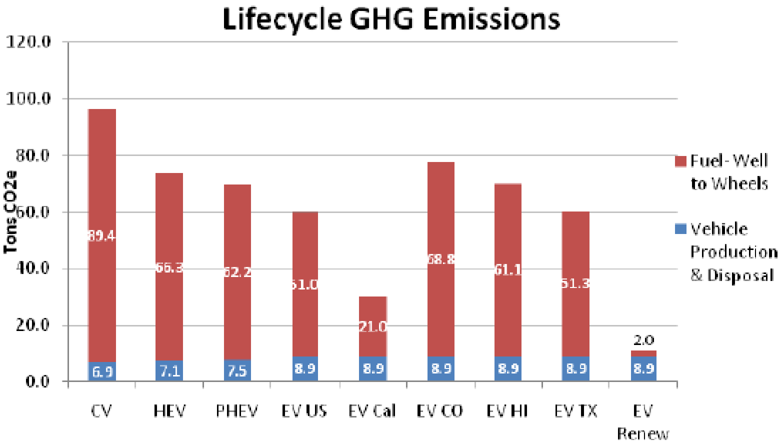


Figure 1(a) lifecycle GHG emission for vehicles

There is an agreement that lacking IEVs are the main weakness which impedes the EV penetration (Alan L. Porter, 2013; W. E. Matters & E. Policy, 2010; Nigro, 2011). By providing a rich infrastructure network of EVs (IEVs), the EV range could be extended by receiving charging opportunities to EVs after the batteries are depleted; the battery size could be decreased, and the cost of EVs could be lowered by applying battery leasing or direct battery size reduction.

Some argue that the current battery capacity of EVs is enough for the actual demand of urban driving without providing extra charging utilities. However, some surveys in the US show that there is a significant gap between the real need of driving range of EVs and the expected driving range of EVs induced by customers' range anxiety. The demand of average driving distance in urban areas was relatively low in the US with only 33 miles (Ralston & Nigro, 2011). A recent survey shows that 90 percent of US respondents drive 75 miles or less than 75 miles per day (Traction, 2011). The range could be achieved by most BEV and PHEV cars nowadays. If we fully charge our EVs at home every day, there is virtually no need to recharge the battery during daytime. The daily vehicle driving distance distribution in the US is predicted as shown in Figure 1(b) (O'Keefe et al., 2011), according to the 2001 National Household Transportation Survey (Collia, Sharp, & Giesbrecht, 2003). This figure shows that the longer traveled miles, the lower probability of occurrence of the driving distance. Hence, from the driving range requirements, it is not necessary to have large volume of additional public charging stations, besides home charging once per day. This point can be proofed in another way as shown in figure 3 (O'Keefe et al., 2011). Actually, for an EV with 100 miles driving range, there are only 8% recharging events would happen to extend the driving range. It means there are 92% driving events won't require external charging stations or swapping stations. However, another study shows, the average expected driving range for drivers in the US are 300 miles on a single charge answered by 63 percent of respondents (Traction, 2011). The significant discrepancies between actual daily driving range and expected demand are caused by a psychological reaction called "range anxiety", which means people are feared to drive on EVs which have insufficient driving range to reach their destinations.

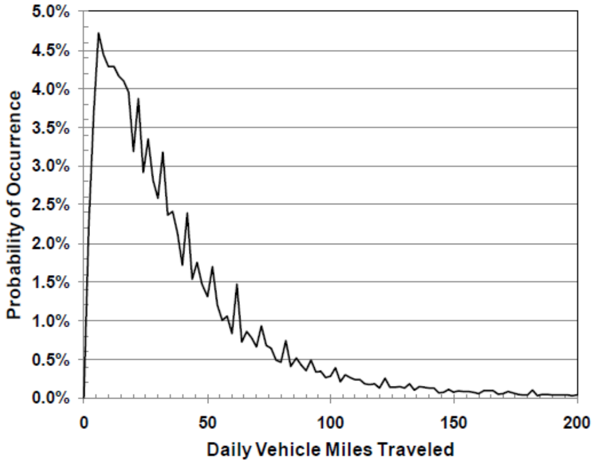


Figure 1(b) probability of daily vehicle miles travelled(O’Keefe et al., 2011)

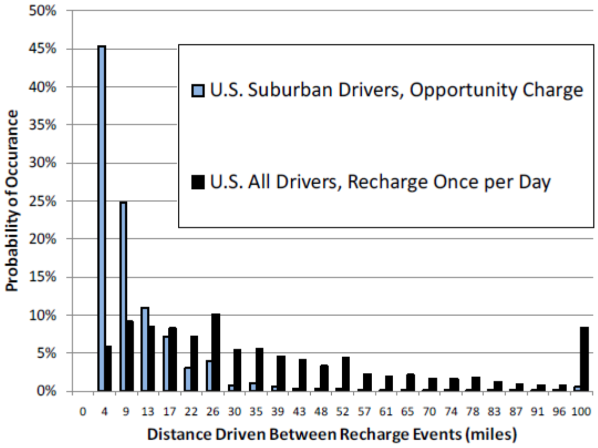


Figure 1(c) probability density function: daily recharge events (miles) (O’Keefe et al., 2011)

Therefore, providing external IEVs is essential to overcome the obstacle of customers’ “range anxiety”, extend the driving range and potentially decrease the battery size and further reduce the upfront cost of EVs. As shown in figure 1(c), If we can provide ubiquitous opportunities of charging batteries after every trip in the suburban areas of the US, the need for EV driving range will drop dramatically, as shown by the opportunity charge distributing bars (O’Keefe et al., 2011).

There is no clear prioritization of IEVs either due to competing technologies and their associated lobbying activities (Alan L. Porter, 2013). The lack of a dominant technology leads to the lack of investment in IEVs by private sectors, which severely limits the growth of EVs. Some governments have deployed the IEV network by public private partnership projects to examine their convenience and practicability, either in a nationwide scale or a community scale, for instance, Israel, the US, Germany and Japan, etc.. Most of these deployments are demonstration projects which are aimed to evaluate and test possible EV systems. Charging stations are deployed more widely than swapping stations or hydrogen refuelling stations. The tested vehicle types are also limited to a few, for example, the PHEV Nissan Leaf, FCEV Chevrolet Volt, etc. In reality, not every configuration of EV designs has been tested; besides, not every configuration of infrastructure has been deployed, either. Therefore, to what extend and what type of IEVs are needed are still unknown and are difficult to determine (W. E. Matters & E. Policy, 2010), since both the EV designs and IEV deployment are in the nascent stage. An analysis which can comprehensively investigate the technical hurdles and social barriers for all possible deployment of both EV and IEV designs are required.

This project is aimed to investigate the technical hurdles and social barriers for the development of EV systems for urban areas. The research question is thus formulated as: what is the reverse salient of electric vehicle system for urban mobility? To answer the research question, we first explore all possible electric vehicle configurations by morphological analysis in case of omitting important possible EV designs; then determine the reverse salient by two pathways: a literature review; and expert interviews based on the morphological analysis results.

Reverse salient is a notion used to describe the drawback parts in a whole technological system. It could be specific components or sub-systems; or social influencing factors which are holding back the performance of the whole system. RS indicates the critical parts which should be deal with to improve the entire system's performance. Based on the investigation of RS, innovators and entrepreneurs can predict the potential growth path of the whole technological system. Due to the current uncertainties and strong social sensitivity of EV system, RS could be a legitimate theory to support our research in identifying the improvement path of every possible configuration of EV system. Morphology is a typology method used to structure problems, organize brain storming and predict future designs. We will use morphology to investigate all possible configurations of EV systems.

According to the research ideas, the sub-questions are formulated as:

1 What are possible configurations of EV systems?

1.1 What are the key parameters and values for the physical EV designs?

1.2 What are the key parameters and values for the IEV deployments?

1.3 What are possible configurations of EV system?

2 What is the RS of EV systems for urban mobility?

2.1 What is the RS of EV systems for urban mobility, based on a literature review?

2.2 What is the RS of EV systems for urban mobility, based on morphological analysis and expert interviews?

2.3 What are the similarities and differences between the results from question 2.1 and 2.2?

3 What is the main RS of electric vehicle system in China and how to improve it?

3.1 What is the main RS of electric vehicle system in China?

3.2 Which policy strategies can be suggested to the China’s central government?

The expected contributions of this project are in two aspects. First, as academics, we will learn if the combination of MA and expert interview is suitable for investigating RS in the automotive market; the goodness of using MA to realize the theory of RS in a large-scale technological system. This will contribute to the method development of the reverse salient theory. Practically, the result of this research will provide insights about possible configurations EV systems for the urban areas to the stakeholders in the EV system. The revealed RS will help the automotive industry to make better business strategies. It will also support governments to make better policies towards the EV development in order to fulfill a more sustainable society.

In the following sections, initially in section 2, the literatures of EVs are reviewed to find out the research gap in current literatures. The RS theory and morphology method are reviewed to analyze the suitability of their application in this research. Subsequently in section 3, we proposed and explained our research method as morphological analysis, literature review and expert interviews. In section 4, we introduce the system diagram of EV development, the structure and working principles of BEV, HEV, FCEV and the deployment of their related infrastructures. The main morphological analysis of exploring all possible EV system configurations are illustrated in Section 5. Based on the findings, the results of two research pathway: a literature review and expert interviews, are analyzed respectively to conclude the RS of EV systems for urban mobility. Ultimately, the conclusion and recommendation for future researches are proposed in the last section.

2 Literature review

In this section, we will discuss the meaning of investigating RS in EV systems. First, previous researches about EV analysis are reviewed to find out the research gap. Then we discuss the advantages and disadvantages of using MA and RS for technological analysis respectively. Based on that, we propose and discuss the benefits of combining MA with RS to explore the drawbacks of EV system designs in our project.

2.1 Researches about EV analysis

There are a few researches about forecasting the development trend of vehicles by different methods. Most researchers only focus on one type of EV or IEV deployment, for instance, the charging stations; HEV and BEV deployment, rather than a comprehensive analysis of all possible vehicle designs and IEV deployments. Multiple methods have been used to predict the future of EVs, such as system dynamic, data envelopment analysis, forecasting innovation pathways, etc., However, some methods are proofed to be not suitable for EV forecasting while others only focus on a general picture of the future of EVs instead of a detailed design oriented projection.

(Tudorie, 2012) wrote her master graduation thesis about assessing the suitability of using the method, data envelopment analysis (DEA), for forecasting the vehicle technology development. The research results showed that DEA is not suitable for predicting vehicle technology since it did not involve external factors. EV’s strong dependence on socio-economic factors makes it cannot be solved by merely quantitatively methods. Therefore, a qualitative method which contains both technological and social influencing factors is in need.

(Alan L. Porter, 2013) used patent analysis to study the innovation pathway of EVs. Eight groups of innovation factors are found based on patent analysis and expert workshops. They concluded that development strategies and innovation pathways are different among the three groups of countries: the US-Europe, China-Japan and India. They also discussed the EV development in three different target segments: urban mobility, military vehicles and larger long range vehicles. This research gives us a clear map of the entire development pathway of EVs. It also pointed out the importance of infrastructures for EV development in urban areas and some critical issues in the development of urban mobility. We will refer to its finding of critical sub-systems of vehicles and infrastructure factors in our morphological parameter designs in section 4.

(Morales-Espana, 2010) used system dynamics to explore several uncertainties towards the electric vehicle diffusion. The research results show that the diffusion level of PHEV is expected to be higher than EV since PHEV can take the advantages of internal combustion energy (ICE) which realizes the requirement of long range driving and utilization of existing infrastructure. This research analyzed the problem in a broader perspective and successfully involved social-economic factors. However, it only stayed in a big picture of EV adoption but did not explore detailed EV/HEV designs and their

IEV deployments. Besides, system dynamics seems to be more as a problem structuring tool than a technology forecasting method.

Hence, there is still a research gap in identifying detailed HEV system designs by considering both technological and social influencing factors. Another appropriate method for IEV system investigation is in demand.

MA is an appropriate method for exploring all possible configurations considering both EV designs and IEV deployments. While RS theory can be good lenses for us to explore potential social and technological influencing factors that hindered the diffusion of each configuration. These two concepts could be complementary to each other in the application of EV system analysis. MA combing with expert interviews could be a tool to broaden the application of RS in identifying innovation direction or future development of technological systems. We will illustrate these ideas in the section 2.2 and 2.3.

2.2 Morphological analysis for exploring potential designs

2.2.1 The origin and development of MA

MA was originally pioneered by (Zwicky, 1967), the Swiss astrophysicist and aerospace scientist, as a method used to probe the structure of a problem by identifying and investigating the total set of possible relationships or “configurations” to help generate ideas for innovation and/or discovery (Ritchey, 1998; Shurig, 1984). It is also called morphologies or morphological analysis (MA). The term morphology comes from Greek word, “morphe”, which means the study of form or shape. It is related to the typology construction, but more generalized in the form and conceptual range (Ritchey, 1998).

MA is pictured as a cross-impact matrix that depicts non-numerical relationships among technological, social, economic and political elements, however, “unlike cross-impact, morphology is intimately concerned with structural relations and thus more truly structural than correlative in nature” (Porter et al., 1991: 66).

Originally, MA was a general tool for typology generation. The “object” in question can be physical (e.g. an organism or ecology), social (e.g. an organization or social system) or mental (e.g. linguistic forms, concepts or systems of ideas) (Ritchey, 1998). Due to its strong ability for exploring potential typologies, MA is also seemed as a comprehensive method for technological forecasting. It was widely used in discovering new design configurations in astrophysical objects, for example, the development of jet and rocket propulsion systems, and the legal aspects of space travel and colonization (Ritchey, 1998). Based on the concept developed by Fritz Zwicky, the Swedish Morphological Society further broadened the application of MA to policy analysis and future studies.

2.2.2 Advantages in design exploration

Axiom design is another method for exploring design configurations. (Suh, 2001) separate the design process into four domains: customer domain, functional domain, physical domain and process domain, as shown in figure 2.2.2. Within each domain, there are different requirements for customer, functioning, physical design and design process. A robust design process is defined as a zigzagging process among the four domains through designing right domain's parameters based on the left side's parameters and modifying them to abide by the two design axioms: 1 Independent Axiom: Maintain the independence of FRs; 2 Information Axiom: Among those designs that satisfy the independence axiom, the design that has the smallest information content is the best design. The two design axioms are also used to judge the goodness of a design.

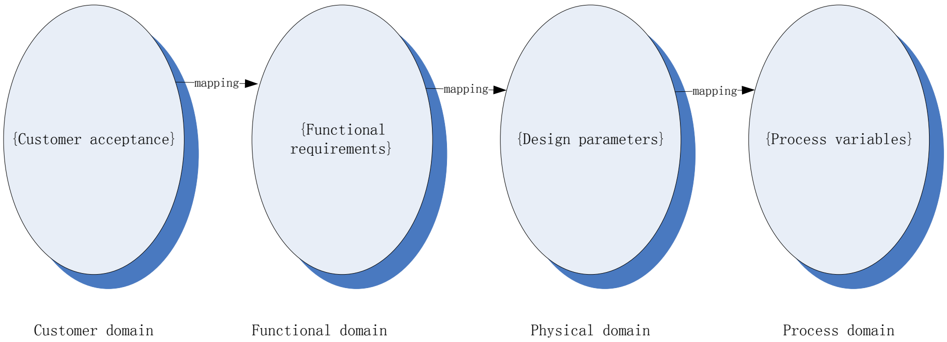


Figure 2.2.2 Four domains of the design world (Suh, 2001) p10

However, the design sequence of axiom designs maybe too idealistic. First, customer demand is hard to define precisely, due to personal differences, data availability and future uncertainties. Second, customer's demand can be shaped by the market. Customer requirements have limited impacts on product designs. Instead, most of the time, technological transitions were induced by technology innovations and social influences such as public policy encouraging and political environment changes.

In the deployment of EV, technological progress and innovation was initiated from the auto industry, which might be not acceptable by customers shortly, but in the long term, it might be viable through marketing or policy encouraging. For example, the cooperation of public and private sectors can also influence the automotive market by imposing a particular type of vehicle and its infrastructures. Hence, it is not easy to start the design process precisely from considering customer requirements (CRs). Just like the development of EV system, there are multiple available designs of EVs and IEVs in the market or in a demonstration phase, which are not designed initially to meet the needs of clients. Therefore, axiom design is biased if the CRs are defined incorrectly.

Compare to axiom design, MA is more suitable for exploring EV system designs in this project since it has boarder application and can be used more freely. The parameters in MA can be designed according to particular problem setting. It can focus on a part of the process of a product design instead of the whole process.

2.2.3 Limitation in technological forecasting

Compare to other technological forecasting methods, such as causal modeling and formal mathematical methods, MA not only can contain strong social-political dimensions or self-reference among actors, but can also allow uncertainties inherent in problem complexes (Ritchey, 1998). Besides, MA can exhaustively examine all possible solutions for a problem which human minds usually are incapable or expensive to track. It also encourages us to abandon preconceived patterns of solutions, which avoids us from otherwise overlooking, rejecting and inclining to eliminate possible solutions (Porter et al.1991:106).

However, when applying MA in technological forecasting, it only considers possible design configurations based on current states without arguing possibilities of future innovation or improvement of particular configurations. If we take future uncertainties of technology change or social influences into account, the result of MA cannot give an accurate prediction. We will further propose RS as a complement theory to improve MA in technological forecasting by providing extra criteria to analyze MA results in section 2.3. The combination will give more information to inventors or entrepreneurs about the critical problems in each configuration. And based on the possibilities of improvements of each problem, we can conclude the optimal configurations.

2.3 Reverse salient and technological forecasting

RS is a theory used for identifying specific components which fell behind the performance of the whole system. Improving these drawbacks will bring a better technology system performance. Hence, RS was widely used to predict potential innovation schemes in history, for instance, the invention of and alternating current transformers. This theory has been used by many in literatures; however, no systematic method has been developed for practicing RS in technological analysis. Most researches only use this concept to analyze the history of technological system development. In this section, we will review the applications of RS in literatures initially. Based on that, the shortages of the current application of RS are described. At last, we will discuss the effectiveness of combing RS theory with MA method in our project.

2.3.1 The origin and development of RS

The concept of ‘reverse salient’ was borrowed from the military term which was used to identify “the section of an advancing battle line, or military front, which has fallen or been bowed back”. The bowed part becomes the weakness of the entire army and leads to the failure of the full force action. Hughes found the typical pattern of technology development by studying the history of electrification development in western countries during 1880 to 1930 (Hughes, 1983). Similarly as the meaning in military usage, RS in large scale system can be defined as:

RS can be identified as the technological drawback from a particular component or sub-

system which hold back the performance of an entire technological system. Besides the internal dynamic of technology system, external factors like economic or political factors which shape the technology can also become the RS of the technological system.

The concept of "reverse salient" is often confused with technology imbalance or "disequilibrium" and "bottleneck" in economic or economic history studies, but "reverse salient" is preferable in analyzing the evolvement of a large-scale technological system, because the concept "refers to an extremely complicated situation in which individuals, groups, material forces, historical influence, and other factors have idiosyncratic, causal roles, and in which accidents, as well as trends, play a part" (Hughes, 1983: 79). In comparison, ""disequilibrium" suggests a relatively straightforward abstraction of physical science, and "bottleneck" is geometrically too symmetrical" (Hughes, 1983: 79), which does not always affect the system's output performances and may do not need correction as "reverse salient".

Among large-scale technology systems, relatively drawbacks of a particular component or sub-system will hold back the development of the entire technology system, as a 'reverse salient' of the technology system. "The improvement of one component in a system will reverberate throughout the system and cause the need for improvements in other components, thereby enabling the entire system to fulfill its goal more efficiently or economically" (Hughes, 1983). 'Reverse salient' can be not only formed by the internal dynamic of technology system, but also by external factors that shape the technology like social and economic circumstances. Hence, to identify 'reverse salient', a system approach should be used.

2.3.1.1 The importance of applying system approach when identifying RS

System approach refers to a technology development method which focuses on the entire sociotechnical system that contains both internal dynamics of technology and external factors which interact with the technical system. The internal dynamics of technology includes both systematically related technical sub-systems and technical components. Besides technical dynamics, socio-economic factors also affect the development of technological systems. By applying system approach, "reverse salient" will be found out as critical problems, which will be improved by modifications or inventions in order to improve the whole system performance.

Based on the assumption that history of all large-scale technology can be studied effectively as a history of systems (Hughes, 1983), Hughes studied the history of power system in terms of technology and society in the western countries from 1880 until 1930 in order to construct a model for studying technology systems in general. "System" in this book is loosely defined as interacting components of various kinds, such as the technical and institutional, as well as different values (Hughes, 1983). Therefore, in the book, Hughes not only focused on the internal dynamics of technology, but also described the external factors that shape technology. Through comparing developments in three different countries: US, Germany and UK, over a period of fifty years (Hughes, 1983), the overall structure of the history of energy system was outlined as four phases: the invention and development of a system, technology transfer from one region and society to another, system growth, substantial momentum and planned system by managers. Among each phase, various “reverse salient’ was discovered by inventors, engineers, and other professionals that called for correcting actions to make the system function optimally or achieve system goals (Hughes, 1983).

Multiple cases proofed that identifying and correcting “reverse salient” under a “system approach” contributes to the success of inventor-entrepreneurs. Inventor-entrepreneur here refers to the people who see the invention of technology by a system approach including technological-social-economic contexts instead of in a solely technological point of view (Hughes, 1983). In the period of invention and development of a power system, inventor-entrepreneurs took the center stage. Hughes attributes the concept of “system approach” to Edison, an inventor-entrepreneur who has designed the entire system of incandescent electric lighting, for he preferred to invent systems rather than components of other person’s systems (Hughes, 1983). Edison noticed the “reverse salient” of the incandescent lighting system as the durability of filament, and future invented a high-resistance filament that solved the problem which contributed to the first commercialized incandescent lamp. Edison’s system approach is due to two considerations. First, if the inventor created only a component, he remained dependent on others to invent or supply other components (Hughes, 1983). Second, Edison found that imbalances among interacting components pointed up the need for additional invention (Hughes, 1983).

The importance of “system approach” and “reverse salient” can also be drawn from “the battle of the current” in the early 1880s. It is worth noting that “reverse salient” can be defined simultaneously and differently by inventors and engineers in an attempt to improve the situation (Hughes, 1983). And sometimes radical innovation can be the best solution for solving critical problems, compared to incremental innovations. Edison had identified the cost of distributing electricity by wire or cable as a substantial “reverse salient” in the systems he was creating. “The central station would not find a market unless the cost of distribution was further reduced” (Hughes, 1983). A three-wire system was invented to solve the high cost of low-voltage distribution and transmission problems (Hughes, 1983). In addition, storage batteries were also tried by Edison. However, the Edison’s electric system became a loser at last, giving way to the radical invention of an alternating current transformers invented by Ganz &Company of Budapest. Although the idea of designing a transformer system was firstly initiated by a French man, Lucien Gaulard and a British man, John D. Gibbs instead of Ganz &Company, the invention of transformers were only awarded to Ganz &Company. The patent conflict between Gaulard and Ganz &Company led to a life tragedy of Gaulard, and Hughes used the case proofed the significance of applying “system approach” in developing a technological system.

2.3.1.2 Technological, economic and political RS

Examples of technological and economic RS have been illustrated before in 2.3.1.1. The low resistance of the filament of an incandescent lamp was the technological RS. And the high cost of electricity distribution by current electricity was the substantial economic RS for the failure of Edison's distribution system.

Besides technical and economic RS, political policy can also become RS. After the success of the central station in NY, Edison tried to transfer the electric light system to London and Berlin around 1882. The central station is an electricity supply system which would distribute electric light to the public. This is different from generating plants or isolated stations, which can only be used by their owners. The technology transformation received different results from London and Berlin. The system did not survival in London but received significant success in Berlin. Hughes reviewed the reasons for the results as "The most penetrating explanation for the failure in London and the success in Berlin is neither technological nor economic; it is political" (Hughes, 1983).

Not the technology transferred that has failed in the Holborn Viaduct Station of London, but the frustrating influences from a series of legislative acts, especially those from parliamentary constraint, decided the failure of the electric light central station in London. Elaborately, the Electric Lighting Act in 1882 from the parliament of UK largely frustrated the development of Edison's central station. The Act allows private companies or local authorities to set up supply systems. Britain owned a large amount of coal sources during the 19 century. The total production of coal reached 50 million tons in 1850 in UK. The abundant coal sources made the low price of gas at that time. Facing the rich and cheap gas sources, the municipal government in London had already invested a lot of money in gas lighting. The low price of gas lighting and restrictive laws discouraged the investors for the Edison's electric central station. In addition, local governments also did not believe that the new technology could bring profit as what the gas lighting did. It was seemed risky to invest taxpayer's money into a technology which has not yet been fully proved. Therefore, it is the contradiction and conflicting interests in the parliament of Britain constrained the development of the central station in London.

On the opposite, the central station received big success in Berlin. 42,000 incandescent lamps were installed in the lighting plant at Friedrichstrasse 85 in 1884. Two years later, another station at 80 Mauerstasse were installed. The success of the installation in Berlin results from the sufficient power of the Deutsche Edison company and the alliance investment banks and industrial interests which allowed them to persuade the local authorities to clear the way for their business.

After the construction of the concept, "reverse salient" has been widely used as a framework to study the history of large-scale technology system like electric vehicle system, mobile music business, PVS plastic entrenchment and personal computer technology. The literatures mainly employed two kinds of methods, history study and empirical study. A few empirical studies have been done to find out quantifiable measures of “reverse salient”, which contributes to another research direction. Besdies, Dedehayir used bibliometrics citation analysis analyzed the number of citations of “reverse salient” and assessed the significance of “reverse salient” in the study of technological systems (Dedehayir, 2009). Dedehayir also revealed that 46 articles had applied deep conceptual analysis of “reverse salient” in comparison to 51 articles with shallow analysis (Dedehayir, 2009).

2.3.2 “Reverse salient” application by history study

Several literatures applied the “reverse salient” in studying history of various technology systems. However, most of them only employed “reverse salient” as a tool to study the drawbacks of a particular technology system, but seldom improved the theory. Takeishi& Lee proposed that the music copyright management institution is a “reverse salient” in the large technological system of mobile music business, which has influenced the development of mobile music businesses in different ways in the two countries: Japan and Korea (Takeishi & Lee, 2005). Hoyer studied the development system of battery by using “reverse salient”(Hoyer, 2007). In the article, he used the concept of radical innovation for correcting “reverse salient” in the existing system to explain the change from electric vehicle to fuel cell technology in the vehicle technology system (Hoyer, 2007), which contributed understandings of energy storage inventions in the vehicle domain. It is worth to note that radical innovation is not a new solution for correcting “reverse salient”, it was concluded as an effective solution for solving “reverse salient” in Hughes’s book by giving the example of alternating current invention defeated direct current power station (Hughes, 1983). Hence, both articles didn’t contribute to the theory development of “reverse salient”.

The concept of “reverse salient” also has been broadened to fit the particular study objective of PVC industry in the article of Mulder & Knot. They mentioned that they had found a flaw in the concept of “reverse salient” since it does not include external factors. Therefore, they included outside influences as well as negotiation processes between different sub-systems by combing a network-oriented perspective with “reverse salient” concept (Mulder & Knot, 2001). However, the standpoint was not well proved since, in the Hughes’ system approach theory, external factors like institutional and economic systems were also seemed as sub-systems or components which could become a “reverse salient” in the entire technology system. Which factors can be defined as external factors is mainly decided by the system boundary which has to be defined at the beginning of the research. Hence the network oriented view of Mulder & Knot cannot be attributed as a complement of “reverse salient”. Sawhney & Wang used the “reverse salient” studied the bottlenecks within sub-systems of motor carriers, railroads and water carriers of the overall transportation system (Sawhney & Wang, 2009). They also examined the problem in a meta-system level, which defined the interfaces between motor carriers, railroads and water carriers as bottlenecks, and future developed a solution as containerization (Sawhney & Wang, 2009). This is an improvement of the application of “reverse salient”, and future researchers could use this meta-system level concept to investigate “reverse salient” from the interfaces among components or sub-systems.

2.3.3 Empirical applications of “reverse salient”

Dedehayir reviewed the literatures from the set-up of the concept of “reverse salient” until 2008 by bibliometric analysis. He found two disciplines of “reverse salient” publications. The first discipline is about retrospective analysis of “reverse salient” in historical systems (e.g. telegraph, railroads and railways) or prospective analysis in new systems (e.g.photo-voltaic energy, electric vehicle) (Dedehayir, 2009). Another general research discipline, which cites the concept frequently, is that of telecommunications, both in the modern and historical contexts. The articles dedicated to modern telecommunication cover topics such as wireless services and information and communication technology, which due to complex sociotechnical systemic structures are predicted to continue publishing works citing the concept (Dedehayir, 2009). Dedehayir demonstrated that incorporating strategic management with “reverse salient” would be an unexploited research area since the study field of strategic management has sparingly cited the concept of “reverse salient” (Dedehayir, 2009).

Besides the application of “reverse salient” as a tool to study several technology history, a few empirical studies improved the concept, which developed means to measure the magnitude of “reverse salient” by studying “the co-evolution between PV games sub-system with two hardware sub-systems: the CPU (central processing unit) and the GPU (graphics processing unit), respectively” (Dedehayir & Mäkineif, 2008). Dedehayir used the temporal change in speed gap between PC and GPU and between PC and GPU to indicate that PC sub-system is the “reverse salient” in the PC system. The “reverse salient” was measured by an absolute measure of “reverse salient”, which is the disparity between sub-systems and remains (Dedehayir & Mäkinen, 2011). Based on the findings, Dedehayir& Mäkinen improved the measures of a reverse salience by adding a proportional measure of “reverse salient”, which determines the ratio of the absolute performance gap with respect to the highest level of performance attainable by the technological system (Dedehayir & Mäkinen, 2011). A “reverse salient” typology was also proposed to help define different types of “reverse salient” as progressive, reorienting, intermediating and prohibitive RS (Dedehayir & Mäkinen, 2011). The typology helps to classify different types of “reverse salient” by quantifiable method. It would be significant for applications in pure technological system. However, one limitation of this paper is this approach cannot be used to analyze not quantified, abstract and complex social factors or systems. Researches about applications by using this typology are needed, and enlarge this typology with social-economic factors is also a research direction which has not been explored.

2.3.4 Application limitation of RS theory in technological forecasting

This theory has been used by many in literatures. Many technological system transitions proofed that identifying RS can give inventors and entrepreneur’s potential hinds of the innovation path and further achieve a better technology and take over the market; however, the application of RS in literatures only stays in the stages of post hoc analysis instead of analysing potential technological transitions. To improve the application of RS in technological forecasting, a systematic method needs to be developed. And MA could be a suitable pre analysing approach for applying RS. By literature review and expert interviews, RS could be identified for each configuration from the MA results.

2.4 The meaning of combining MA with RS

The combination of RS and MA in technological forecasting could make up the gap of lacking a proper method for exploration the optimal EV system designs by considering both technological and social influences. MA is a suitable method for exploring all possible configurations considering both EV designs and IEV deployments. While RS theory can be good lenses for us to explore potential social and technological influencing factors that hindered the diffusion of each configuration. These two concepts could be complementary to each other in the application of EV system forecasting.

On one hand, RS can help MA to analyze optimal designs more comprehensively by considering key drawbacks of every configuration and further identify innovation paths and predict technological trends. On the other hands, MA combines with expert interview is a good tool to practice RS theory in order to find out optimal solutions for technological innovations. Many used RS theory only as a notion to analyze some technological system development history. There is no tool being developed for the application of RS in technological forecasting. MA can be used to structure the technological system before analyzing RS in each configuration. This will make RS more specific in one particular design configuration instead of discussing the technological system broadly. By inserting RS concept into MA method, RS will have a physical medium to practice its concept and also enlarge its application value in technological forecasting realm.

Hence, combing RS theory with MA method will benefit both of them. MA can get theoretical support in technological forecasting from RS. RS will receive a medium for applying itself in more realms of technological analysis. The combination will improve the application values in technological forecasting of both. It also contributes to the field of technological forecasting by providing a stronger theory-method frame.

3 Research method

There are several available methods of forecasting emerging technologies. They can be classified into three categories as shown in table 3 (Porter et al., 1991:65).

Table 3 Technological forecasting methods by (Porter et al., 1991:65)

Category	Definition	Forecasting Methods
Direct	Direct forecast of parameter(s) that measure an aspect of this technology	Expert Opinion (Delphi, Surveys, NG), time series analysis, trend extrapolation (growth curves, substitution, life cycle)
Correlative	Correlative parameter(s) that measure the technology with parameters or other technologies	Scenarios, lead–lag indicators, cross impact, technology progress function, analogy
Structural	Explicit consideration of cause-and-effect relationships that affect growth	Causal models, regression analysis, simulation models (deterministic, stochastic, gaming),relevance trees, morphology

Every method has its advantages and disadvantages; it is unable to judge the superiorities of one over another. But it is necessary to determine if one method is appropriate in certain problem situation. As reviewed in section 2.1, EV diffusion is not solely related to technological innovation but also strongly social influenced by global and local environment factors, political policies, energy prices and customer demands. These uncertainties imply forecasting the development trend of vehicles extraordinarily complex and quantified method cannot solve the problem comprehensively. Hence, a qualified method, which can analyze the technical structure with social factors, is appropriate for this research.

In our research, we use morphology to explore all possible EV system technological configurations. Based on that, we will find out RS which includes both technical and social influencing factors of each configuration by two rounds of four expert interviews.

3.1 Morphological analysis

Morphology is a method used to probe the structure of a problem by identifying and investigating the total set of possible relationships or “configurations” to help generate ideas for innovation and/or discovery(Ritchey, 1998; Shurig, 1984). It is also called morphologies or morphological analysis (MA). It is related to the typology construction, but more generalized in the form and conceptual range(Ritchey, 1998).

MA is pictured as a cross-impact matrix that depicts nonnumeric relationships among technological, social, economic and political elements, however, “unlike cross-impact, morphology is intimately concerned with structural relations and thus more truly structural than correlative in nature” (Porter et al., 2011)(Porter et al., 1991: 66).

The process of morphological analysis can be summarized as six steps(Porter et al., 2011; Ritchey, 1998; Zwicky, 1967) (Porter et al.1991:105):

Step 1 Concisely formulate the problem need to be solved.

Step 2 Choose all parameters that might be of importance to the solution of the given problem.

Step 3 Define all alternate possibilities of each parameter.

Step 4 Construct the morphological box or multidimensional matrix, which contains all of the potential solutions of the given problem, which generate the exhaustive checklists of all combinations of parameter possibilities. Each combination is a solution configuration.

Step 5 Eliminate configurations due to reasons of incompatible, contradictory, meaningless or other reasons like impracticality or high expenses by applying a cross-consistency assessment (CCA).

Step 6 Scrutinize and evaluate each configuration from the remaining solutions in turn in an analogous manner with respect to the objectives that are to be achieved.

Step 7 Select the optimally suitable solutions and apply the solutions practically, provided the necessary means are available.

One limitation of MA will be its relatively time-consuming thoroughly analysis of all configurations, compare to other methods. In the original process of MA, all the configurations will be analyzed after step 4 without applying step 5, which is difficult for analyzing problems with relatively more parameters, because the configurations of possible solutions will increase rapidly as the number of parameters increase. For instance, if there are 3 critical parameters to the concept to be solved. Each parameter contains 5 possibility values. The number of all configurations is 5*5*5=125. If one more parameter with 3 possibilities is added in this context, there will be 5*5*5*3=375 configurations in total, which is twice bigger than the original solution spaces.

To solve the limitations of MA, (Koberg & Bagnall, 1974) suggested that an analyst can select and exam random choices of all configurations in order to avoid meaningless analysis. But this did not solve the problem radically. (Rhyne, 1981) and Ute von (Reibnitz, 1987) developed an extension step in the process of MA. The concept of this extension is to weed out configurations with incompatible or contradictory relationships in the total solution set in a pair-wise manner. This step can largely lighten the complexity of analyzing all possible solutions. (Rhyne, 1981) named the process as Field Anomaly

Relaxation (FAR), whereas (Reibnitz, 1987) named it internal consistency analysis. In this paper, we will call the extension step as cross consistency assessment (CCA), which was named by(Ritchey, 1998) based on the concern that MA also include complex policy spaces and scenario spaces. Besides, a few computer aided tools like a program in TOOLKIT, Excel, etc. can assist the process of CCA.(Ritchey, 2006) proposed a computer aided morphological analysis tool to support and improve MA process.

Morphological analysis will be employed as a research method in this project to examine all possible EV system design configurations. Compare to causal modeling and formal mathematical methods, MA, is a good alternative and more suitable for this project, since it not only can contain strong social-political dimensions or self-reference among actors, but can also allow uncertainties inherent in problem complexes (Ritchey, 1998). Besides, MA can exhaustively analyze all possible solutions for a problem which human minds usually are incapable or expensive to track. It also encourages us to abandon preconceived patterns of solutions, which avoids us from otherwise overlooking, rejecting and inclining to eliminate possible solutions (Porter et al., 2011).

The limitation of MA will be its relatively time-consuming thoroughly analysis of all configurations, compare to other methods. Therefore, to guarantee the do-ability of the project in a certain amount of time about 5 months, we narrow down the problem boundary to analyze the interfaces of physical EV designs and IEV designs for urban areas in order to employ feasible number of parameters instead of analyzing it in a boarder boundary including highway and other irrelevant parameters.

3.2 Literature review

Literature review is used in three aspects: first, it is used to explore a suitable methodology for our project, as illustrated in section 2. Through reviewing existing researches about EV forecasting, we figure out the research gap in this domain. Based on that, the development and application of the reverse salient theory and morphological analysis are reviewed. The advantages and disadvantages of the two theories are discussed. The idea of using the combination of the two theories to investigate the optimal EV system design are proposed. Second, the literatures about EV configurations and IEV deployments are reviewed to design the key parameters of morphological filed. This part is shown in section 4; at last, literature review is also used to find out key RS for each EV system configuration. We further confront the RS found from literatures with the results from expert opinions to conclude comprehensive and unbiased results.

We systematically find out literatures we need in this project. The sources of EV forecasting researches and the main parameters and values in the morphological field and the RS of each EV system design are from two ways: key words searching in databases of Scopus, Google Scholar and web of science; explored literatures from the database of the research from (Alan L. Porter, 2013). (Alan L. Porter, 2013) studies the innovation pathway of EV development by bibliometric study. It provides us good resources of valuable literatures covering both scientific and market researches.

For the RS theory part, as a start, the book of Hughes(Hughes, 1983) which initially proposed the concept of RS was studies as a knowledge base of reviewing other literatures about RS. After that, review papers about “reverse salient” were searched. (Dedehayir, 2009) did a bibliometric analysis of “reverse salient” which quantitatively analyzed the number of papers and the literature stream of “reverse salient” concept from 1993 to 2009.This article was used as a decent starting point to explore other literatures about RS. The remaining literatures were found by searching the citation relations with existing papers and key words searching in separate databases: Scopus, Google Scholar and Web of Science. The key words being searched is “reverse salient”. The literatures, which do not contribute to the concept significantly, result from only using the concept of “reverse salient” as a background introduction rather than a dominant concept, were filtered out in our reviews.

For the review of MA, we use the same searching strategy. Firstly the origin of MA, (Zwicky, 1967), was studied. Then we follow the citations from a review paper about general morphological analysis of (Ritchey, 1998)to find out more literatures about MA in design configuration exploration and technological forecasting applications. The key words being searches are “morphology” and “morphological analysis” with “technology forecasting” and “design”.

3.2 Expert interview

Expert opinions will be collected by individual interviews in order to confront with our result of RS of each EV system configuration from literatures. The interviewees of this research are one expert in FCEV industry, two experts who committed to EV industry and one expert in policy analysis of IEV deployment. There will be two rounds of interviews. In the first round, we aim to find out expert opinions about the RS in each EV system configurations and their opinions about possible improvements and possibilities of the improvement. After that, we will collect the result and analyze the consistencies and inconsistencies between different interviews. We will also discuss the consistencies and inconsistencies between literatures and industry expert opinions. In the second round, we will show our findings to all experts and obtain information about their reactions and explore further information to complement our arguments. Interview questions, as shown in appendix 1, are designed before each round of interview as preparation.

4 EV system analysis

4.1 System diagram and EV related activates

To analyze the development trend of EVs comprehensively, a system diagram of the EV development is drawn, as shown in figure 4.1(a). Internally, EV sub-system and infrastructure sub-system construct the whole system of EV development. The two sub-systems interact and complement with each other in order to make EV functioning and diffusing in the market. The output of this system is CO_2 emission, the number of EVs and vehicle price, etc. The output factors show the performances of EVs which in turn influence the decision making process among the arena of the stakeholders of EV. Besides the manipulation of decision makers, multiple external factors which cannot be controlled by the system actors are critical factors for the system. For instance, a suddenly scientific discovery of alternate energy, increasing of oil prices or a third world war may accelerate the development and diffusion speed of EVs. In the following sections, we will introduce the system diagram in detail.

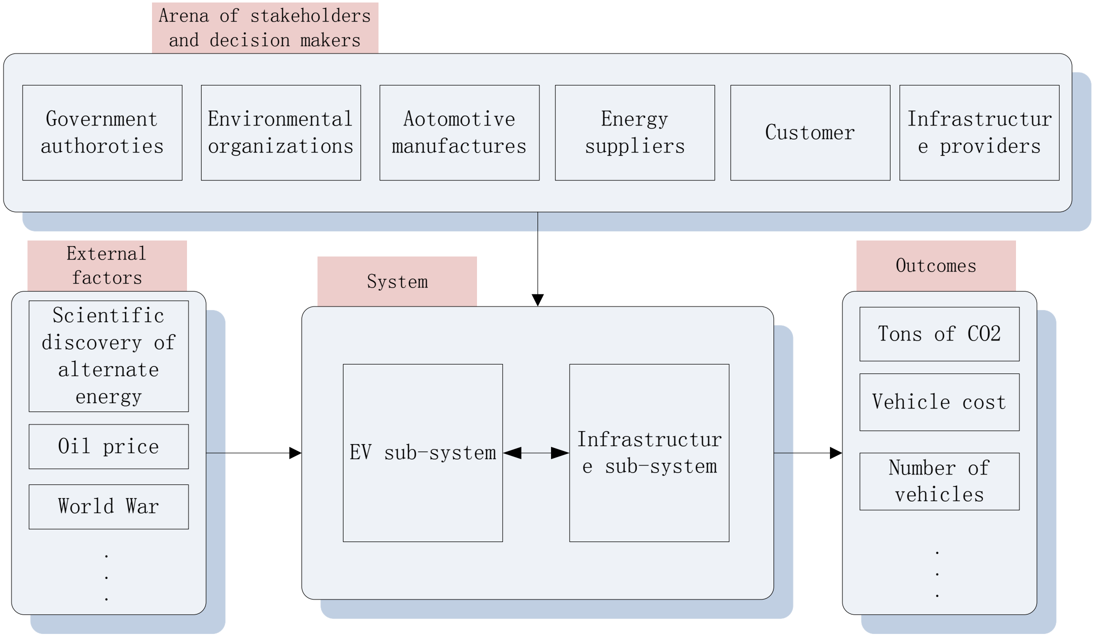


Figure 4.1(a) System diagram of EV development

The essential activities associated with EV development was defined by (Narich, Stark, Schutz, Ubbink, & Noom, 2011) by two groups: the demand-led activities and supply-led activities. Based on the finding, (Nigro, 2011) draws upon the work and proposed a complete activity chart by adding the activity of “develop charging infrastructure”, as shown in figure 4.1(b). Multiple stakeholders can be identified through this chart. The right supply-led activities need the cooperation among automotive 1, 2 and 3 tire manufactures, electricity providers, IEV constructors, service providers and IEV maintenance companies. These actors could be overlapped such as one company can be responsible for designing, constructing and providing charging and maintenance services. On the left demand-led activities, the main interactions are among customers and charging and maintenance service providers.

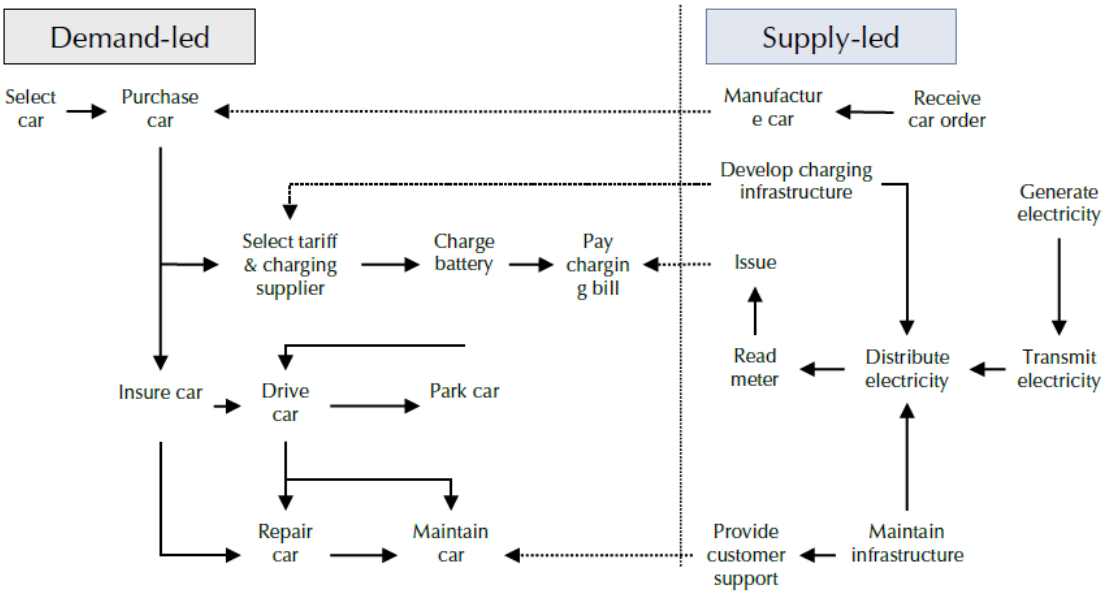


Figure 4.1(b) PEV related activities (Nigro, 2011)

4.2 Key influencing factors of the development of BEVs and HEVs

Actually BEV was invented half century before the appearance of conventional ICVs. The development of BEV has experienced the early inventions from 1800 to 1880, the golden age from 1880 to 1990, two development peaks during two world wars, several fade out periods and the revival period after 1970 (Hoyer, 2007). Several critical issues can explain the ups and downs of BEV's development. They also implied the key factors including internal and external factors which interacted with and impacted EV development.

The development of EV is closely related to the development of batteries. The first tricycle EV applied the Plante's lead battery as its power source in 1881, since then, electric boat, tricycles with LiB were invented one after another. Since then, several alternate battery designs were considered as alternate energy storage system for EVs, like Lithium ion, NiMh, etc. Many researchers are working on the improvement of battery performances in order to realize better EVs.

The development of EVs also benefits from other technical breakthroughs which improve EVs functional performances. Most technical breakthroughs, like regenerative braking invented in 1887 and hybrid electric vehicles (HEVs) invented in 1990, appeared during the last twenty years of 1880s.Notably, these technologies still form the basis of EV technologies even now, after a hundred years. These technological breakthroughs allowed BEVs to be widely used for public transportation like taxi fleets in London, Paris and New York before 1990s. 1n 1903, New York had 4000 registered vehicles, in which

53% are steam powered, 27% gasoline ICEs and 20% EVS (Høyer, 2008). Nowadays, new technologies like in-wheel motor, the combination of batteries and fuel cells, vehicle to grid (V2G) concept and other ongoing technological researches are stimulating the development of EVs.

External factor like high cost of production, and internal functional performances of driving range limitation are main drawbacks of EVs. Although the success as public transportation, BEVs were luxury goods only for nobles during their golden age; the golden age of BEVs didn’t last long, because Ford-T model beat BEVs and achieved market dominance in 1909 by providing a cheaper price and better driving performances. Since then, EVs temporarily disappeared.

World war is blasting fuse which will influence the growth of EVs dramatically. EVs went back to the stage and reached their two peaks during the two world wars. During the WWI (1914-1918), since most ICVs were taken part in the war effort, the shortage of gasoline in cities triggered the usage of EVs. USA as the main production of EVs, had 50000 EVs exported to European countries for private transportation by the end of WWI; the main buyers at that time were Norway, Sweden, South Africa and Japan(Hoyer, 2007). Besides, the abundant electricity resources and electric power stations in Europe also pushed the EV’s revival. As the finish of the WWI, EVs were totally disappeared temporarily after 1920 until the appearance of the WWII in 1939. This time, the usage of EVs reached its peak in European countries and Japan. The world war issues indicate that the shortage of gasoline is a key external factor which would boom EV development. During the post-war period, due to short of gasoline, “Tama Electric Power cars” were invented and became popular in Japan for a short time.

Government policy can also stimulate the development of EVs. During the WWII, German authorities promoted the use of EVs by executing tax-exempt policy for EVs. 30000 EVs were used for postal services during that time. The Great Britain also promoted the EVs by strong marketing campaigns, resulted in 60000 EVs for milk and bread delivery in 1940. Nowadays, many European countries’ and USA’s governments have issued policies to stimulate the development of EVs and HEVs.

Environmental concern is another important external factor for EV development. The environmental issues hadn’t drawn attention of EV pollutions until 1960, by when Rachel Carson published a book named “Silent Spring”, which focused on environmental pollution problems caused by pesticide chemicals used in agriculture. The local problem of too much air pollution in urban areas were debated by authorities. Then, in 1970, more debates about energy problems enlarged the air pollution problem to a bigger importance level. To achieve the environmental protection objective, EVs development became active again since then. In 1976, US congress planned to reach all EVs in 2000. Around 1990, the problem reached a bigger volume as global pollution.

4.3 EV operating principles

4.3.1 BEV/HEV operating principles

In contrast to irreversibly consumed in the case of combustion fuels, the chemical substances in the batteries of BEV or HEVs convert energy by reversible chemical reactions. During charging the batteries, they can convert electrical energy into chemical energy. During discharging the batteries, the stored chemical energy will be turned back into electricity for use to drive the wheels

Battery electric vehicle (BEVs) solely depends on electrochemical battery and electric motor (EM) to power wheels. While HEV, which use both electric and combustion power as energy sources, can be divided into several categories based on different vehicle architectures. For instance, Plug-in hybrid electric vehicles (PHEVs) are vehicles which are any HEVs that can be directly connected to the electrical grid for charging their batteries; Full HEVs which can only be driven for short distances by electric-only power and the batteries cannot be recharged on the grid; and extended range EVs (EREVs) cover PHEVs which can only be driven by EM, as opposed to regular PHEVs which can be driven by either the ICE or EM (Serra, 2012).

Noticeably, the electrochemical batteries of EVs are the energy storage system of vehicles, and there are multiple choices for the battery composition, e.g. lithium ion, nickel metal, lead acid, etc. Different composition will also lead to different levels of cost-effective and driving performances.

There are doubts and debates about if EVs will achieve total environmental gains, since in most countries, around 70% electricity comes from grid dominated by nuclear and fossil fuel production (Høyer, 2008).However some clarified that even so, EVs still provide opportunities to largely decrease the negative impacts on environment locally and globally than conventional ICVS. As shown in figure 1(a) (O’Keefe et al., 2011), if we use renewable resource for the electricity used in EVs, BEVs show the lowest well to wheel GHG emission; although PHEVs partially use ICEs, the total GHG emission is still 27 tons smaller than ICVs.

4.3.2 FCEV operating principles

Fuel cell is the part which can provide propulsive power to FCEVs. Similarly as battery, a fuel cell also generates electricity via an electrochemical reaction. “However, a battery holds a closed store of energy within it and once this is depleted the battery must be discarded, or recharged by using an external supply of electricity to drive the electrochemical reaction in the reverse direction. A fuel cell, on the other hand, uses an external supply of chemical energy and can run indefinitely, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air).” (FuelCellToday, 2013b)

There are several different types of FCs, but they are all based on a same chemical reaction design. Fuel cell is a kind of battery which transfers chemical energy into electric energy via a reverse reaction of electrolysis of water with oxygen or other oxygen agents. The primary components of a fuel cell are bipolar plates/ electrodes with anode and cathode, electrolytes, catalyst, and other hardware.

The primary operating principle is shown as figure 4.3.2 (Sakurambo, 2007). There is an entrance for fuel from the left anode plate of the fuel cell. The fuel will firstly get contact with the catalyst on the anode plate. The catalyst will oxidize the fuel and turn it into an ion and an electron on the anode plate. The electrolyte is specially designed so only ion can pass through it. So the freed electron will travel through an external wire from the anode plate to the cathode plate and therefore create direct electricity current. During this period, the anode gets a negative charge, and the cathode gets positive charge. The ion which passed through the electrolyte to the cathode plate will reunite with the electron came from the wire. Then the reunited fuel will react with oxygen or oxygen agents which come from the right entrance to create water or carbon dioxide.

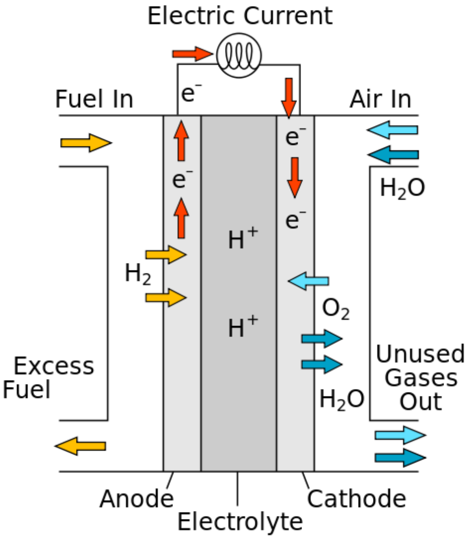


Figure 4.3.2 Fuel cell operating principle (Sakurambo, 2007)

Usually the hydrogen, methane from natural gas, methanol or propane can be used as the fuel for FC; the anode catalyst can be precious fine platinum powder, and the cathode catalyst is nickel. Different types of FCs can be distinguished by the electrolyte to be used.

The FC has been successfully used in material handling vehicles which accounts for over 90 % of the niche market (FuelCellToday, 2013b). The PEMFC technology is widely used for buses which have taken place in the US, Canada, Japan and Europe. However, FCs is seemed limited used in light duty vehicles nowadays. But FC is going to change the market of auto mobiles since many auto companies have planned to start commercial sales of FCEVs by 2015.

4.4 EV Infrastructures

In this section, we will talk about three types of infrastructures for EVs: charging stations, swapping stations and hydrogen refueling station. All of them can extend the driving range of EVs and may provide opportunities to reduce the overall cost of EVs. The characteristic of them decide they can be used in different ways to assist EV deployment.

4.4.1 Charging stations

Charging station can provide charging devices for connecting EVs to the grid and recharge their batteries. It can be classified into different types based on charging current level, charging standards and locations. The form 4.4.1 shows all possible types of charging stations and their charging times (Ralston & Nigro, 2011).

Form 4.4.1 charging levels included in Society of Automotive Engineers (SAE) J1722 standard (Ralston & Nigro, 2011)

Level	Current	Electric Potential Difference (V)	Current (A)	Power (KW)	BEV Charging Time (Minutes)			
					3.3 kW charger	7kW charger	20kW charger	45kWc harger
Level 1	AC	120	12/16	1.4/1.92	1020			
Level 1	DC	200-450	80	36	-	-	72	-
Level 2	AC	240	80	19.2	420	210	72	-
Level 2	DC	200-450	200	90	-	-	-	20

4.4.2 Swapping stations

The other infrastructure solution for EVs is implementing swapping stations. Battery swapping is a technology motivated by the limits of the longtime charging. It makes fast charging batteries possible by exchanging a fully charged battery pack in the swapping station. The battery ownership is transferred to battery swapping companies, EVs customers can rent and switch batteries by purchasing the swapping services in swapping companies.

Battery swapping has many benefits for the EV deployment. First, the switching time is on average 59.1 seconds which is much shorter than the DC fast charging time of 30 minutes (Abuelsamid, 2010). Second, it can provide EVs unlimited driving range if a rich battery swapping stations are available. Third, the swapping process is easy that the driver does not need to get out of the car. At last, since the battery ownership is transferred from traditional buyers to swapping companies, the upfront cost of EVs is decreased, which means that the price of EVs are lower or equivalent than ICVs.

Battery swapping did not receive much attention at the early 2000 (MacCarley, 2000). Nowadays some companies like Better Place, Tesla Motors and Mitsubishi Heavy Industries are working in swapping technologies (Loveday, 2010). The first commercial deployment of swapping station network is built by the Better Place with the Renault Fluence Z.E., the first electric car enable with switchable batteries in Israel. At the end of December 2012, 17 battery swapping stations were operated in Denmark. However, current news shows that Better Place has been bankruptcy in Israel in May, 2013. The main reason for the financial difficulties results from high investment and low market penetration of EVs.

4.4.3 Hydrogen refuelling stations

As shown in figure 4.4.3, based on the logistics of the hydrogen production, there are generally two types of hydrogen refuelling stations: on-site station and off-site station (FuelCellToday, 2013a). On-site producing will use the material like natural gas or LPG, naphtha, etc. to produce hydrogen within the stations, then compress and storage hydrogen into the refuelling dispensers in order to refuel FCVs. Off-site stations do not need to produce hydrogen themselves, but require external shipping facilities of either truck or pipeline for delivering compressed hydrogen from gas companies to the refuelling stations. The on-site production can provide the same energy, compressed hydrogen, as the centralized hydrogen generation; hence we do not consider the logistics of hydrogen production and transpiration in this research; but rather consider the interfaces between the FCV infrastructures and physical FCVs.

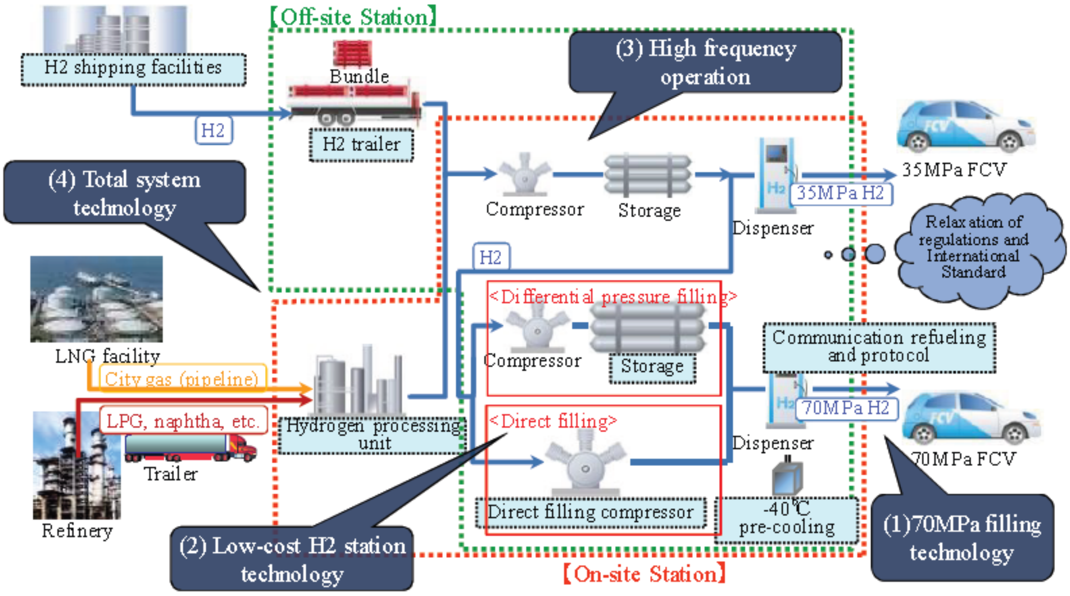


Figure 4.4.3 Hydrogen refuelling infrastructures (FuelCellToday, 2013a)

5 Morphological analysis of EV system configurations

5.1 Key parameters and values exploration

The key parameters and values of EV system are constructed by two parts: the parameters and values of the physical EV designs and their associated infrastructure designs. The key parameters and values are designed based on literature reviews and expert interviews. Based on our research question, the chosen criteria for EV system parameters are defined as:

Criterion 1: the importance of the parameter in designing an EV or infrastructure which makes the EV distinguishable from conventional ICVs. The parameter could be core components which is essential to the fundamental objective of motion. There are thousands of subcomponents, such as transmission, camshafts, crankshafts, chassis, seats and so forth in a vehicle, however, they will not be discussed in the research.

Criterion 2: the combination of the values from all the parameters can help identifying different categories of EVs and EV systems;

Criterion 3: if there are multiple sets of EV system parameters, the one with the minimum parameters will be chosen.

Criterion4: only the interface parameters are chosen for the final EV system parameters. It means, if the parameter in the EV physical design cannot influence different ways of infrastructure that is being needed, the parameter is not included in the EV system parameter set. On the other side, if the parameter in the EV infrastructure designs cannot influence the chosen of different types of EVs, the parameter is not included either.

Firstly we found out detailed technological key parameters of EVs and infrastructure of EVs (IEVs) from literatures. After consulting with experts, the key parameters were adjusted. Some parameter values are modified to values in a higher level. Finally, according to the four criteria and expert opinions, the final parameters for the EV system are defined.

5.1.1 Key parameters and values of the physical EV design

The initial key parameters and values of EVs are designed based on literature reviews, as shown in form 5.1.1 (a). We refer to all available vehicle designs in the market based on the data set from (Tudorie, 2012). This data set gave detailed information about current EV technological parameters in the market or the trial. Besides, we also consider the values which are not used in the market, but may have potential application in the future, such as inductive charging. After consulting with EV experts, the key parameters were decreased into a higher level instead of discussing the detailed battery substances, as shown in form 4, since all the substances are possible to be used in a battery, it is unnecessary to separate them.

The key parameters are energy storage type and electric motor type. The values for energy storage type could be a battery, fuel cell, flywheel, super capacitor or several hybrid types of the combination of multiple energy storage ways. If we discuss it in a lower level, we could get many options for battery or fuel cell, such as lithium-ion battery, lead acid battery, etc. In case we neglect any important discussion about the RS of EV system. We included all the lower level substances of energy storage type initially.

Form 5.1.1(a) Initial key parameters and values for EV design

Energy storage type	Electric motor type
Lithium-ion battery	Permanent magnet AC synchronous motor
Nickel-metal hydride battery	3-Phase Permanent Magnet Synchronous Motor
Nickel salt battery	Permanent magnet
Lead acid battery	AC synchronous
LiFePO4	DC brushless motor
Co-Ni-Nm Li-ion	Asynchronous
NiNa molten salt	fly-wheel mounted motor generator
Ion Phosphate - Li-ion	2 DC brush motors
Li-ion polymer	AC induction motor
Proton exchange membrane fuel cell	
Flywheel	
Super capacitor	

The parameters are adjusted by the expert interviews. One expert indicated that it is unnecessary to distinguish different types of battery or fuel cell because all types are possible to be used in EVs. For instance, all types of batteries are possible to be used in EVs as a battery pack; the efficiency performance of each type of battery depends on the way of usage and detailed configuration of EV. When we talk about the technological or social RS of these battery types, they have mutual RS, such as high cost, low capacity and safety issue, etc. Two experts pointed that Lithium ion battery was widely used in the current EV designs; it is also seemed as one of the optimal choice for battery. However, they cannot say the other battery types are not applicable in EV designs. Therefore after the expert interviews, the values of energy storage type were adjusted into a higher level as battery, fuel cell, flywheel, super capacitor and multiple hybrid types.

Besides, there is another parameter related to how, and where the electric motor is installed is also important for EV designs. In general, there are two ways to allocate EM: centrally allocated and distributed allocated. The centrally allocated EM is connected through a gearbox to the drawing wheels, just like conventional combustion engine. The EM can also be distributed directly in or near the wheel, such as in-wheel motor. There are many factors are affecting how efficiency the motor is. The efficiency depends on the configuration. For instance, the brushless motor tends to run more efficiently in very high speed, but it is not the case for AC induction motor, which tends to run more efficient at the medium and low speed. So it is more about the efficiency levels from each configuration, because all configurations would work. Hence we include the new parameter: “configuration” into our analysis, as shown in 5.1.1 (b).

Table 5.1.1 (b) Final key parameters and values for EV design

Energy storage type	Electric motor type	Vehicle configurations
Battery	AC induction motor	Parallel
Flywheel	Permanent magnet synchronous motor	Series
Super capacitor		EM directly power the wheel
Proton exchange membrane fuel cell		

5.1.2 Key parameters and values of the IEV deployment

The parameters and values for IEV deployment are collected and designed from literatures of IEV design and reports of IEV demonstration projects.

Form 5.1.2 key parameters and values for IEV design

Type of infrastructure	location
Hydrogen refuelling station	Home
Level 1 charging	Apartment complex
Level 2 conductive equipment (EVSE) (120 VAC 40 amp)	Commercial facility
Level 2 Inductive equipment (120 VAC 40 amp)	

DC fast charging	
Battery swapping	

5.1.3 Key parameters and values for the EV system

According to the criteria 4, the combination of all the parameters should be useful to distinguish different types of EVs, however, the parameter “electric motor type” does contribute to this point, since which EM is chosen is not significant to influence the value chosen of IEVs. For instance, the full battery vehicle with AC induction motor or permanent magnet motor can both be charged by charging stations and battery swapping station. However, the parameter, vehicle configuration, abides by the criteria 4, since different configurations may lead to different needs of infrastructures. For example, if the ESS type is “battery and gas tank”, then if the vehicle configuration is parallel, the infrastructure could be either charging stations, swapping stations and gasoline /diesel station, but if the vehicle configuration is a series, the battery of vehicle is necessary to be charged by infrastructures. So the final key parameters and values for the EV system are shown in form 51.3.

The vehicle configuration refers to the interaction way between the energy storage system and the vehicle propulsion system. There are four values being defined here. First, “only EM without ICE” refers to the configuration which only includes EM in its vehicle propulsion system, this configuration exists in full electric vehicle and full fuel cell vehicles. Second, “parallel hybrid” represents the hybrid vehicle which contains both ICE and EM, and both ICE and EV ultimately drive the wheels in an identical manner (Serra, 2012). This configuration could be traditional HEV or a plug-in HEV. The battery in a conventional HEV can be charged from regenerative breaking or ICE, but it cannot be charged by outside energy power. The PHEV can be charged by outside power grid. Third, “Series hybrid” also includes both ICE and EM; however, only EM directly drives their wheels, with ICE as a complementary energy source to charge the battery. This is an EM biased configuration. Extended range EV is an represent of this configuration. Four, “Series/parallel hybrid” is a configuration between “Series hybrid” and “parallel hybrid” in terms of the EM biased degree. It refers to vehicles which allow both ICE and EM to drive the wheels. ICE is also a complementary energy source for the battery, such as the Toyota’s Hybrid Synergy Drive.

Form 5.1.3 Infrastructure parameters and values

Energy storage type	Configurations	Infrastructure type
Battery	Only EM without ICE	Level 1 charging
Flywheel	Parallel hybrid	Level 2 charging
Super capacitor	Series hybrid	DC fast charging
Fuel cell	Series/parallel hybrid	Battery swapping
Battery and fuel cell		Hydrogen refueling station
Battery and gas tank		Existing gas station
Battery and flywheel		
Flywheel and super capacitor		
Battery and super capacitor		

5.2 Morphological field and cross consistency assessment

According to all parameters of EV system, all possible designs could be defined by the combination of values in each parameter. Each parameter could be described as a single vector which includes different discrete values. The vector for energy storage type is X_{EST}= {battery, fuel cell, flywheel, super capacitor, battery& full cell, battery& gas tank, super capacitor & flywheel, flywheel& battery, super capacitor& fuel cell}; The vector for vehicle configurations is Y_C={Only EM without ICE, parallel hybrid, series hybrid, series/parallel hybrid}; the infrastructure vector is: Z_I={Level 1 charging station, level 2 charging station, DC fast charging, battery swapping, hydrogen refueling; gasoline or diesel refueling}. Every value from each parameter can combine with any other value from the other two parameters to become a configuration for EV system. For example, if we pick up all the second value from each parameter, the combined configuration is $V_{(2,2,2)}$={X_{EST}{fuel cell},Y_C{parallel hybrid}, Z_I{Level 2 charging station}}={Fuel cell, parallel hybrid, level 2 charging station}. The configuration is not applicable, since fuel cell cannot be charged by electricity and a fully fuel cell vehicle does not have ICE in its configuration.

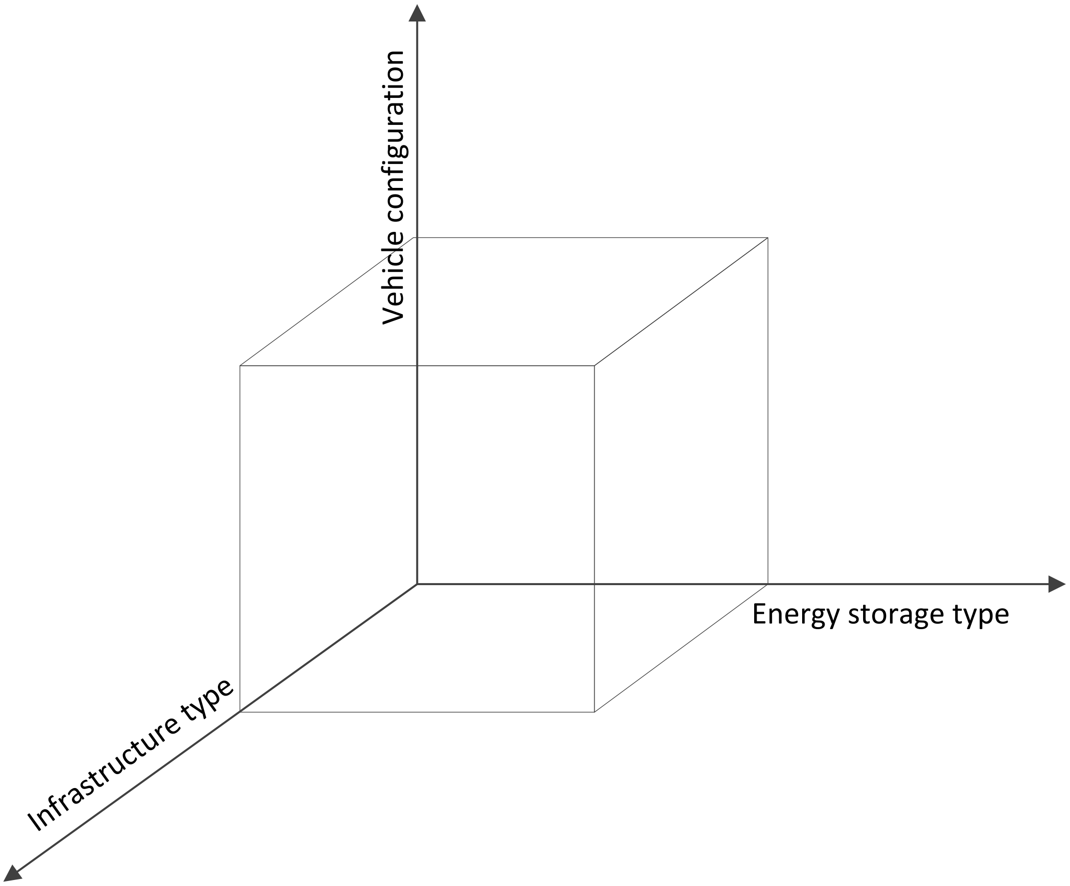


Figure 5.2 Morphological field of EV system

There are 9*4*6=216 EV system configurations in total. There are some inconsistencies in the combination of different values, such as hydrogen refueling station cannot be applicable with full battery vehicles. If we confront all the values of the three parameters, there will be a three dimensional confrontation matrix. We checked and filtered out all the inconsistent configurations. The final results are 45 possible EV system configurations, as shown in Appendix II.

These configurations are classified into 7 types in the section 5.3. Based on these classifications, a further discussion about the RS of each type of configuration is analyzed in the section 6.

6 Reverse salient of the EV system and results validation

In this section, we will discuss the RS of EV system based on two pathways: reviewing previous literatures, and consulting EV experts based on the configurations investigated from morphological analysis. At last, we confront the results from both pathways to validate the results. At last, a conclusion about RS of EV system for urban mobility is given to assist the investigation of further strategies in the next section.

6.1 RS from literature reviews

In this section, we discuss the RS based on reviewing previous literatures. First, we shortly described the way of literature collection and reviewing. Then, we introduce the results in five sub-contents: RS of BEVs, HEVs, FCEVs, super capacitor and flywheel EVs and related infrastructures for EVs. The category of various EV is based on the information given by all the literatures being reviews. The results from literature reviews gave us a general idea about what will be expected to acquire from the latter expert interviews. Based on the assumptions, we can further find out the similarities and differences of both results in order to validate the research results.

6.1.1 Literature review description

For exploring the RS from literatures, 34 literatures are reviewed from both the mind mapping database of (Alan L. Porter, 2013) and key words searching from databases of Scopus, Google Scholar and Web of Science. Some literatures cover the discussion of drawbacks of multiple types of EV; others only focus on one or a few types of EV. The HEVs have been discussed the most within all the papers. Some focus on the technical feasibility of EVs, others pay more attention on social challenges for EV adoptions. The summary and analysis of the reviews literature are demonstrated in the following contents.

6.1.2 RS of BEVs

From literatures, the RS for BEV type vehicles for urban mobility are in three perspectives: technical, economic-effective and social perspectives. From the technical side, the RS of BEV comes from driving range limitation, short life span of the battery and safety problems. From the economic-effective perspective, the RS of BEV are high overall cost. From the social perspective, the RS of BEV are low customer acceptance results from range anxiety, driving habit change, safety concerns and high purchasing burden; the lack of charging infrastructures; and the lack of coordination with current power grid.

- Technical performance drawbacks

The technical RS of BEV is focus on the battery. (Serra, 2012) Indicate that EM of EVs is a fully matured technology. The battery is the one key component that is underdeveloped. Many claimed the battery capacity; life span and safety problems still need to be improved by technical innovation and optimization, which will be illustrated respectively as below. But some disagree with this point, (W. E. Matters & E. V. Policy, 2010) indicate that the battery technology does not need to be more advanced for the average customer; the current performance, such as the energy density and torque, are enough for urban driving demand. The real problem for BEV diffusion results from low customer acceptance. We will explain the customer acceptance in the discussion from a social perspective.

- ✓ Low battery capacity and short driving range

The technical RS of BEVs mainly results from the energy storage system, the batteries equipped on the vehicles. The first technical barrier of BEV is that the battery capacity is relatively low battery capacity compare to the current performance of ICVs (Phaal, 2002). This will also reduce the driving range of BEVs. However, this point is argued by many researchers who show that the current vehicle battery capacity is far enough for customers' daily driving demand in urban areas (Pesaran, 2010). Therefore, the relatively low energy capacity is not a main drawback for the BEV adoption.

- ✓ Short life span

Life span, which is also called charge cycle, is measured in year as expected battery usage. It shows the amount of time that a battery can be used before it can no longer hold a sufficient charge for its application (W. E. Matters & E. V. Policy, 2010). (Graham, 2001; W. E. Matters & E. V. Policy, 2010; Nemry & Brons, 2010) indicate short life span is one of BEV's technical drawbacks. The existing vehicle battery has a capacity for 300,000 charge cycles. The battery of Nissan LEAF and Chevrolet VOLT both announced that their batteries can reach a life time of 8 years. The short life span indicates that consumers need to pay extra money to replace the battery after certain years of use. This will induce a higher cost of the overall cost of BEVs.

- ✓ Safety problems

Most researchers agree that the optimal battery solution for BEVs is lithium-ion battery, because it can provide the highest energy density. However, the use of lithium-ion battery has potential safety problems. The safety operation of the battery needs a certain range of temperatures, not too high or too low. There will be a heat generated during charge, discharge and ambient conditions. If the temperature gets too hot, there might be the risk of explosion and fire. It will also decrease the performance and life of the battery. Thermal management is a critical technology to protect the battery from being damaged or induce safety problems. However, (Romana, 2010) indicated the current thermal management technology still need to be advanced to provide vehicle batteries which can be functional properly in a wide variety of temperature without affecting the battery performance.

The safety problems still exist. High energy and toxic chemicals pose a risk to battery vehicles (Dinger et al., 2010; Kizilel et al., 2008; Romana, 2010). Many lithium-ion battery accidents show us the lithium-ion battery is not an absolute safety chemical safety solution for the vehicle battery. The fire hazard of the luxury Karma PHEV from Fisker

Automotive forced the company to recall 239 of its vehicles (JENSEN, 2011); Chevy Volt batteries caught a fire during its safety tests ("Auto safety chief denies sitting on Chevy Volt warnings in heated hearing," 2012); a crashed UPS jet carrying lithium ion batteries explore the risk of transporting lithium them (*Garthwaite*, 2011). Other types of batters also have fire and explosion risks. Besides, other options do not show as good performance as lithium-ion. For instance, the lead-acid battery has the lowest energy density among all the options, and it will lead to an extremely big size of the battery to achieve a comparable depleting range as lithium-ion battery.

Besides, a recent study about lithium ion battery shows that it may have negative impacts on human health and the environment (Associates, 2013). The result shows that the lithium-ion battery with nickel cathodes and solvent-based and cobalt electrodes have the most unwholesome to human health and have the most impact on the environment. The impacts to the environment include “resource depletion, global warming and ecological toxicity”, while the impacts to human health are “poor respiratory, pulmonary and neurological effects” (Associates, 2013). Therefore, substitution for the cathode materials are needed, and some metals from the batteries need to be recycled in order to lessen the side effects on human health and environment.

- Low economic cost-effective of the battery

Many argue that the low energy capacity is not a significant issue for urban areas, but rather the low economic-effective of the BEV is the biggest barrier which is blocking the BEV diffusion (Graham, 2001; W. E. Matters & E. V. Policy, 2010; Morales-Espana, 2010; Nemry & Brons, 2010; Pesaran, 2010; Romana, 2010; Tom Hazeldine, 2009). The economic-effective reflects in three main costs: the upfront cost of the vehicle and, maintenance cost throughout the battery life and the replacement cost after the battery life span.

In order to reach a desirable driving range, the battery needs to be designed big and thus more expensive. Compare to ICVs, the higher upfront cost of BEVs and external replacement and maintenance cost of the battery show inferior economic-effective. The high overall cost of the battery will directly influence the customers’ purchasing decision, which is also the main inducing reason of low customer acceptance and constraint the market expansion.

Some researchers do not seem the high cost of the battery as a blocking point for BEVs. A few people argue the overall cost of BEVs may be superior to ICVs since it provides cheaper energy cost by charging electricity rather than consuming petroleum, but it also closely depends on the oil price. If the oil price decreased dramatically, the economic-effective of BEVs would be even worse.

Besides, many people have optimistically predicted the battery cost in the short term, though the results are different. (Pesaran, 2010) foresee that, as the technological improving, the price of the battery will decrease to a comparable level to ICVs by 2015. (Nemry & Brons, 2010) indicated that, by process and components innovation, the battery price is expected to reach 300-400 by 2020. (Hensley, Newman, & Rogers, 2012) mentioned that the cost of lithium-ion battery pack today is approximately $500 to $600 per kWh. It is expected to drop to $200 per kWh by 2020 and to about $160 by 2025. The battery price below $250 per kWh could offer BEVs competitive cost with ICVs, with the gasoline prices at or above $3.5 per gallon.

- Customer acceptance towards the vehicle price, safety concerns and range anxiety

Many have studied the customer acceptance towards BEV purchase. The research result from (Jeeninga, van Arkel, & Volkers, 2002) shows that the customer acceptance is affected by mainly “maneuverability”, “energy noise”, “environmental friendly” and “loading capacity”. Additionally “acceleration” and “reliability” are insignificant. Many researchers pointed out that the poor customer acceptance of the high battery price, range limitation, safety concerns and short life span of the battery are blocking the BEV diffusion.

✓ Vehicle price

The current cost of the battery is 700-1000$/kWh. The high battery costs make the upfront cost of the whole vehicle relatively more expensive than comparable ICVs. The high overall price of the battery also due to the high replacement cost of the battery, since the current technology allows the battery to have more than 1000 deep discharge cycles, which means the battery has a life span of 3 years; so after 3 years, the battery needs to be replaced in for the vehicle.

The high battery cost and short life span might be overcome by technological improvement. (Nemry & Brons, 2010) predict the expected life of the battery could reach 10 years by 2014. And the battery price could be decreased by innovation on the process and components of batteries. The expected costs are $300 to $400 by 2020.

✓ Safety concerns

Besides the high costs of BEVs, which is the most significant factor for influencing customer’s purchase decision, some researchers also claimed that the low customer acceptance of BEV results from safety concerns about the risk of toxic battery chemical leakage during accidents. Some researchers indicate that people do not trust the battery technology as much as their attitudes towards ICVs, because they are not familiar with the driving habit with BEVs. As illustrated earlier, safety problems of the battery are also technical barriers for the BEV; thus not only the customer’s acceptance of the battery is a blocking point, but also the technical safety performance of the battery is still a hurdle for the development of BEVs.

✓ Range anxiety

Another social barrier for BEV diffusion is range anxiety. It demonstrates the customer’s psychological worries of not reaching the target location by BEVs due to the limited depleted range of the battery pack. As discussed previously, many pointed that driving range is not a locking point. Current BEVs can meet most people’s daily driving demand by once fully charged battery during a night (Crist, 2012). (Pesaran, 2010) indicate that not only for urban use of BEVs, even for drivers living in the rural areas of the US, it does not need many range extender infrastructures for BEVs.

The average driving distance demand in urban areas was relatively low in the US with only 33 miles (Ralston & Nigro, 2011). A recent survey shows that 90 percent of US respondents drive 75 miles or less than 75 miles per day (Traction, 2011). The range could be achieved by most BEV and PHEV cars nowadays. If we fully charge our EVs at home every day, there is virtually no need to recharge the battery during daytime. The daily vehicle driving distance distribution in the US is predicted as shown in Figure 1(b) (O'Keefe et al., 2011), according to the 2001 National Household Transportation Survey (Collia et al., 2003). This figure shows that the longer traveled miles, the lower probability of occurrence of the driving distance. Hence, from the driving range requirements, it is not necessary to have large volume of additional public charging stations, besides home charging once per day. This point can be proofed in another way as shown in figure 1(c) (O'Keefe et al., 2011). Actually, for an EV with 100 miles driving range, there are only 8% recharging events would happen to extend the driving range. It means there are 92% driving events won't require external charging stations or swapping stations.

However, another survey shows, the average expected driving range for drivers in the US are 300 miles on a single charge answered by 63 percent of respondents (Traction, 2011). The significant discrepancies between actual daily driving range and expected demand are caused by a psychological reaction called "range anxiety", which means people are feared to drive on EVs which have insufficient driving range to reach their destinations. (Tom Hazeldine, 2009) pointed out public perception as the greatest barrier for EV because they doubt BEVs ability to fulfill their driving requirements. Drivers are not pleased by just meeting the daily driving demand, but rather require extra driving range to fulfill their psychological need. The range anxiety of BEVs not only is due to customer old driving behavior but also results from the lack of infrastructures for BEVs in public areas. Therefore, establishing charging infrastructures can help to lessen customers' range anxiety.

- Lack of charging infrastructures

(W. E. Matters & E. V. Policy, 2010; Morales-Espana, 2010; Romana, 2010) agree that lacking infrastructures are the crucial reason for BEV's low adoption rate, because the relatively low driving range of BEVs needs opportunity charging options in public to extend its range. (Bilotkach & Mills, 2012) indicate that providing charging stations in the leisure destinations would increase the vehicle range. The leisure destination here refers to the locations where customers tend to take a rest and assume the vehicle can be fully charged. Otherwise, if the charging stations are allocated in non-leisure destinations, it cannot extend the vehicle range. Without the range extended charging infrastructures, the BEV's range limitation will still be a server hurdle for its diffusion.

- Lack of coordination with the power grid

Many pointed out the significant influence of the energy charging for BEVs to the power grid will be dramatic after the BEVs are widely diffused. The main reason for this is charging a large number of batteries at the same time period, such as the low peak power period during a night, will break the balance of the power grid. Without explicit regulatory policies between EV charging usage and power grid; or coordination between infrastructure providers and power utilities, the large installation of charging infrastructures for BEVs will face a big obstacle for its large scale diffusion.

- Well-to-wheel GHG emission

Besides all the RS of BEVs described before, there is one interesting point about the well-to-wheel emission of BEVs which are drawn from the literature review. (Plotkin et al., 2002) seems BEV as a very environmental friendly vehicle type since it provides opportunities to potentially significant contribute benefits to the local and global environment. (W. E. Matters & E. V. Policy, 2010; Pesaran, 2010) think the well-to-wheel GHG emission is not blocking point for BEV diffusion if they are produced by green energy sources. Based on the current research results, the emission level of BEVs are the lowest among all types of vehicles. However, these results are based on the data from particular countries, like the US. The results are sensitive to the energy sources being used to generate electricity. Indeed BEVs provide us a chance to use clean energy to power vehicles and produce less emission to the environment, but to what extend can we achieve the environmental benefits is still a question.

Only a few researchers doubt about BEV’s total benefits to the environment. (Associates, 2013) indicated that if the vehicle batteries in use are charged by electricity generated from coal-fired plants, EVs will produce a dramatically large amount of CO_2 emission. Therefore, the W2W emissions of BEVs are sensitive to the power grid mix composition.

6.1.3 RS for HEVs

HEVs share some similar RS with BEVs since HEVs are also using batteries to store energy. Thus HEVs also share the main drawbacks of batteries with BEVs, such as the high battery cost, low energy capacity, low life span and safety problems. The advantages of HEV are it shows better driving performance than BEV. It has longer driving range because ICEs can provide parallel or extended power for the vehicle, after the batteries have been depleted. It shows competitive performance with ICVs (W. E. Matters & E. V. Policy, 2010). But it can also provide less emission opportunities. Most researchers seem HEVs as a good transitioning configuration for future electrification transportation. (German, 2004) claim that HEV is a good transition to FCEV, the completely no emission and extremely efficient electrification vehicle type. Multiple types of HEVs are available in the market, such as conventional HEV, plug-in HEV, range-extended HEV. However, the broad adoption of HEVs is still blocked by some critical problems: high cost, lack of infrastructures in the long term and customer acceptance problems.

- Technical problems

From a technical perspective, HEVs are sharing similar drawbacks of BEVs which are safety problems and short life span (Dinger et al., 2010; Kizilel et al., 2008; W. E. Matters & E. V. Policy, 2010; Pesaran, 2010; Romana, 2010), as explained in last section. These two are inherent battery problems which will impact customer acceptance towards HEVs. Different from BEVs, the drawback of low energy capacity of the battery is made up by the provision of ICEs to provide external power; thus HEVs can achieve longer range which better meets customer demand. Therefore, HEVs do not suffer from range limitation hurdles, especially for urban driving demand (Pesaran, 2010). Although HEVs do not have range anxiety as BEVs do, in the long term, potential range anxiety would appear due to the future urban expansion (Alan L. Porter, 2013)**.** Hence the current technical hurdles for HEVs are short life span and safety problems of the batteries in the short term, and potential low energy capacity which induce customers' range anxiety for the long term.

- Economic-effective problems

HEVs also suffer from the drawback of high upfront cost (German, 2004; Graham, 2001; Greene, Duleep, & McManus, 2004; Markel & Simpson, 2006; W. E. Matters & E. V. Policy, 2010; McManus, 2003; Morales-Espana, 2010; Pritchard & Zickefoose, 2005; Romana, 2010). Because of keeping both the battery and the gas tank, the power train system of HEVs is more complex than ICVs or BEVs, thus inducing high cost, big size and heavy weight problems. Most researchers think the biggest hurdle for HEV diffusion is the high cost. For instance, the economics of PHEVs are influenced by multiple factors. Without knowing the petroleum price, it is difficult to judge the value of PHEV. Different PHEV designs will result in different costs of PHEVs (Markel & Simpson, 2006).

- Customer acceptance hurdles

Besides the concerns about the battery safety and high cost of the vehicle, there are no other significant hurdles for customer acceptance towards HEVs. (Greene et al., 2004) even expressed that "except for the high cost, there is no major market barrier to the success of HEV". Most literatures show positive customer's attitudes towards HEVs. The main reason for choosing HEVs is it is not only environmental friendly, but can also provide similar driving range need as conventional ICVs.

Some proofed that the high cost is not as severe as it seemed through customer investigation. (Graham, 2001) shows that there is a potential market for all HEVS even when the price is 25% higher than comparable ICVs counterparts. Many indicated customers tend to purchase HEVs because it is more environmental friendly. (Jeeninga et al., 2002) studies customer shift attitudes and preferences based on the Rotterdam electrification transportation project, one of the six projects in the ELCIDIS (Electric Vehicle City Distribution Systems) project. The research results show that "maneuverability", "energy noise", "environmental friendly" and "loading capacity" are statistically significant when "suitable for our organization" is excluded. (German, 2004) show that one-third of the potential HEV buyers in the US would purchase an HEV even if the extra cost of HEV overpass the fuel saving. However, it also means that two-third of people do not want to pay extra money for HEVs. (Curtin, Shrago, & Mikkelsen, 2009) studied the factors which affect customer's buying preferences. The result indicates that customer's believe that owning a PHEV can dramatically demonstrate their commitment to the benefit to the environment which will offset the high price of PHEV. Hence, the combination of social and economic incentives is effective to influence customers' purchasing preferences.

- Infrastructure availability is a hurdle for long term HEV diffusion

On one side, (Bilotkach & Mills, 2012) claimed that charging infrastructures is not a hurdle for the short term diffusion of HEV, since either PHEVs or REHEVs do not solely depend on charging infrastructures, but can use existing fuel refueling stations to refuel energy for the vehicle. This largely decreases HEVs' dependence on charging infrastructures. However, on the other side, for long-term adoption of HEVs, charging infrastructures are indispensable for HEVs (Alan L. Porter, 2013). As the adoption of HEVs expanding, more charging plugs are needed not only in commercial locations, but also for apartment complex parking places and employers.

✗ Well-to-wheel GHG emission is not RS for HEVs

Similar as BEVs, the well-to-wheel GHG emissions are not seemed as a hurdle for HEV diffusion (W. E. Matters & E. V. Policy, 2010; Pesaran, 2010; Plotkin et al., 2002). Compare to ICVs, all types of HEVs show superior energy efficiency to some extent. Even for the mild hybrid, because of the use of the battery to retrieve and reuse the regenerative braking energy and provide more efficient accelerating energy, the energy efficiency is improved. Not to mention the plug-in HEV, which allows using electricity to power the wheel and largely reduce its dependence on fuel.

Besides, although PHEVs allow both gas refuelling and electricity charge to provide energy for the vehicles, (Graham, 2001) shows that customers prefer to plug in HEVs instead of refuelling gasoline. There are no other researches about customer charging behaviour of PHEVs, so truly or wrongly, if most PHEV customers have preferences of plugging in their PHEVs, the tank-to-wheel CO_2 emission will not be an RS for HEVs. The large adoption of PHEVs will lead to benefits to local environments.

6.1.4 RS for FCEVs

There are generally two types of FCEVs: on-board hydrogen producing design and off-board hydrogen producing design. The on-board hydrogen FCEV equipped not only a fuel cell, but also a reformer to produce gaseous hydrogen by breaking hydrocarbons from liquid fuels such as CNG (compressed natural gas), ethanol, etc.. The off-board FCEV uses hydrogen as the fuel directly. The reaction within the FCEV will only exhaust water as the only tailpipe emissions (Nam & Giannelli, 2005). We will illustrate the mutual RS of both types of FCEVs and also indicate some specific drawbacks of each type of FCEV.

- Short life span, heavy weight, big size and safety problems of the fuel cell stack

The main technical RS of FCEVs are short life span, heavy weight and big size of the fuel cell stack (German, 2004; W. E. Matters & E. V. Policy, 2010; Natkin et al., 2003; Phaal, 2002). (W. E. Matters & E. V. Policy, 2010) seems FCEVs as the least viable vehicle type among BEVs and HEVs in terms of safety, infrastructure and cost problems. The fuel cell stack is constructed by many small fuel cells. In order to reach a desirable energy capacity, the size of FC stack is usually very big and heavy. (Natkin et al., 2003) claim that the weight of FCEVs are usually 25% heavier than comparable ICV counterparts. Not to mention, the on-board FCEVs, which also include reformer and gas tank to produce hydrogen for the fuel cells, are even bigger size and inefficiency, especially for light duty vehicles in urban areas. This drawback makes on-board hydrogen FCEV fell out of favor from technical perspectives (Nam & Giannelli, 2005).

Secondly, although there are several types of FCs, the most commonly used type for automotive application today is PEM (Proton exchange membrane) (Nam & Giannelli, 2005). The main component of fuel cell, the membrane, and the chemical components have a certain life span; which induce the need of FC stack replacement; thus results in customer acceptance of the high overall cost of FCEVs.

Thirdly, there is also some challenges related to the on-board cryogenic storage for hydrogen (Phaal, 2002). This will need thermal management to control and protect the FCEV in case it will get an explosion during accidents or ambient condition changes. This thermal management technology still needs improvement.

- ✗ Driving range is not RS of FCEVs

Many literatures show that the driving range is not a hurdle for FCEVs, because the current energy capacity of vehicle FC stack can reach a driving range of at least 400 km (Ogden, Dennis, Steinbugler, & Strohbehn, 1995). While BEVs are ideally suited to smaller vehicles and short range driving, such as urban driving, FCEVs can provide comparable driving range and performance with ICEs (McKinsey & Company, 2010). Although FCEVs cannot reach the same energy density as liquid fuels, it is much higher than electric batteries, thus perform longer driving range than BEV counterparts. Therefore, FCEV is seemed as a good choice for long range driving usage.

- Low economics of the FCEVs

The low economics drawback of FCEVs comes from the high cost of FC stacks (German, 2004; W. E. Matters & E. V. Policy, 2010; Phaal, 2002) and also from the high potential costs of developing new hydrogen refueling infrastructures for the off-board hydrogen FCEVs (German, 2004; W. E. Matters & E. V. Policy, 2010). Besides, the upfront cost of the on-board FCEVs are even greater than off-board FCEVs, because of the added complexity of the vehicle with extra cost of a hydrogen production systems/fuel processors (Ogden, 1999).

To compare which type of FCEVs is more economic feasible, (Ogden, 1999) examined and compared the costs of developing the on-board and off-board FCEVs with the consideration of deployment of related infrastructures. The results show that the overall cost of methanol and gasoline FCEVs are comparable with the total infrastructure cost for hydrogen FCEVs. The gasoline on-board hydrogen FCEV will cost $500-1000 more than comparable off-board hydrogen FCEVs. Therefore, although both on-board and off-board FCEVs have high costs drawbacks due to the expensiveness of fuel cells, the overall costs considering related infrastructure expenses of the off-board FCEVs are more economics than on-board hydrogen FCEVs.

- Lack of hydrogen refueling infrastructures for off-board hydrogen FCEVs

The big different between off-side hydrogen FCEV and on-site hydrogen FCEV is the former needs to refuel hydrogen from external sources, the hydrogen refilling stations, but the later can use the current available gasoline stations to fuel the FCEVs and produce hydrogen by the on-board reformer. Therefore, lacking hydrogen refueling infrastructures becomes main RS for the adoption of off-board hydrogen FCEVs (Ogden, 1999). Until now, there is relatively less hydrogen refuelling stations being installed around the world compare to charging stations, although Japan and Germany have planned to develop the commercialized hydrogen infrastructure in the long term starting by 2015.

On the other side, hydrogen infrastructures are not RS for on-board FCEVs, "because gasoline/methanol FCEV can reduce (for methanol) or eliminate (for gasoline) the problem of developing new fuel infrastructure." (Ogden, 1999)

- Local or global CO_2 emission is an RS for on-board hydrogen FCEVs

Most literatures agree that FCEV is the cleanest vehicle type which significantly reduces CO_2 and local emissions (McKinsey & Company, 2010; Nam & Giannelli, 2005; Ogden, 1999; Phaal, 2002; Plotkin et al., 2002), compare to ICVs. (Phaal, 2002) argued that the on-board FCEVs are not as clean as off-board FCEVs, future research needs to study the fuel economics of the two types in order to reduce CO_2 emission.

6.1.5 RS for super capacitor and flywheel vehicles

Compare to BEVs, HEVs and FCEVs, relatively much fewer literatures are discussing the use of super capacitor or flywheel for electrification transportation. Concluded from the available literatures, both of them have critical drawbacks which are hindering their application as the solely energy storage system in vehicles. However, the combination of super capacitors with batteries could be a suitable option for EVs.

Super capacitor is also called ultra-capacitor. Its energy density is inferior to batteries. (Serra, 2012) described "Ultra capacitor's physical storage mechanism considerably limits its energy capacity". Since nowadays, the battery capacity are seemed not enough for customer's driving demand, not to mention the pure super capacitor EVs (Karden, Ploumen, Fricke, Miller, & Snyder, 2007). (German, 2004) suggested that the combination of a small battery with a super capacitor can use the advantages of both of them. The battery pack has relatively low power density. It will be used to meet peak power demand during acceleration and regenerative braking. Ultra capacitor has higher power density compared to battery, but with the limitation of storing a small amount of energy. This combination would allow the super capacitor act as a buffer for the battery. It will provide peak power for short acceleration and regenerative braking by super capacitor, while using the battery pack to recharge the ultra-capacitor and absorb the energy captured during regenerative braking. Noticeable, the battery and super capacitor hybrid type will have the drawbacks from both batteries and super capacitors. Not mention the high cost of the battery, the super capacitor is also very expensive; so high cost is also an RS for the super capacitor EVs or HEVs (Karden et al., 2007).

6.1.6 RS for the associated IEVs

The related infrastructures for EVs are conventional gas stations, charging stations which include slow, medium and fast charging options, battery swapping stations and hydrogen refuelling stations with the on-board refuelling and off-board refuelling types. Besides the traditional gas stations can be used for HEVs and on-board gasoline FCEVs, the rest types of infrastructures are either deficient like charging stations, or commercially non-existent like hydrogen refuelling stations. The battery swapping stations is a blip by the initiator, the Better Place Company. The Better Place is an EV infrastructure company based in based in Palo Alto, CA, which had launched the first large-scale public EV charging network in Israel including battery swapping stations (Morgan, 2012). But the first battery swapping stations was shelved because of the bankruptcy of the company in May, 2013.

- High costs of new infrastructures deployment

All the EV infrastructures have the same RS which is the high cost of new infrastructure development. As researched, the current costs for charging infrastructures are range from 1500 to 2500 Euros per vehicle; in which, home charging requires 200 to 400 euro per vehicle, and public charging needs 5000 euro without considering the power distribution network construction (McKinsey & Company, 2010). Major investment from both public and private sectors is needed for the deployment of charging infrastructures (W. E. Matters & E. V. Policy, 2010).

(McKinsey & Company, 2010) shows positive attitudes towards the cost of hydrogen infrastructures. He predicts the additional costs of FCEVs are comparable to charging infrastructure for BEVs and PHEVs. The costs for hydrogen retail and distribution are estimated 1000-2000 euro per vehicle, including distribution, operation and capital cost for the station itself. A 25% market share of FCEVs requires 3 billion euro investment for their infrastructure in the first decade and 2-3 billion euro per year afterwards. Besides, once the infrastructure is built, no further investment is needed in hydrogen infrastructure.

- Long charging time for electricity charging stations

The long charging time of current charging technology is an RS for the charging infrastructure deployment (W. E. Matters & E. V. Policy, 2010; Phaal, 2002; Romana, 2010).

✗ No technical RS for the hydrogen refuelling stations

There is a demonstration hydrogen refuelling stations being deployed in California, USA. Although hydrogen refuelling stations haven’t been commercialised, many researchers show positive attitudes towards the technical feasibility of it. (Ogden, 1999; Ogden et al., 1995) claimed that there are no technological hurdles for producing, delivering and dispensing hydrogen. All the technologies are well known today. Besides, the economic problem of hydrogen infrastructure is not severe but feasible in the California demonstration project.

- Low diffusion of EVs and uncertainty demand for swapping stations

Swapping stations can provide the fastest recharge service for EVs with less than 2 minutes to replace the depleted battery with a fully charged one (Mak, Rong, & Shen, 2012). Thus battery swapping stations overcome the obstacle of the long time charging of regular charging stations; however, the RS for this kind of infrastructures nowadays lie in two perspectives: the low diffusion of EVs (MacCarley, 2000; Mak et al., 2012); and the uncertainty of battery demand (Mak et al., 2012).

The relation between battery swapping stations and EV diffusion is an egg and chicken problem. Other types of infrastructures and their associated EVs also have this dilemma. Without an established network of infrastructures, so many customers would choose EVs. Without a large diffusion of EVs, seldom private sectors would invest in related infrastructure deployment. The success of swapping stations needs a proper management of the battery inventory requirements (Mak et al., 2012). Without knowing the real-time battery demand, the dispatch of batteries in different locations is hard to manage.

6.2 RS from expert interviews

6.2.1 Interview conduct description

In the process of interviews, we have individually interviewed four experts with three work in the automotive technological and market strategy field and one works in fuel system field. The interviews last on average two hours in the location of TPM, TUDelft, SKF, Utrecht and Inergy, Brussels respectively. The interviewees are:

1 Adam Reedman is the Global Manager in the automotive development centre of SKF automotive. Adam has worked in the field of fuel cell ten years ago, and now he is more focused on the electric vehicle technological development direction. He is professional in automotive technological development. He provided valuable knowledge on the morphological designs and the drawbacks of very detailed technological components or systems. His broad knowledge and interests also gave me many insights about the customers' physiological analysis and the business strategies for the future automotive market. Adam stimulated my interests in broader researches in the future.

2 Roberto Galante is the manager in the innovation strategy and ventures of SKF automotive. He has a solid engineering background in Aeronautical Engineering and fluid dynamics. He is professional in project management, automotive and product

development and innovation management. He has worked in responsible for all aspects of the development/implementation of projects and programs involving department and cross-functional teams focused on the delivery of a product from the design process through a finished state for internal/external customers ("Linked in Profile," 2013). Roberto gave us a broad map of the whole market operation of electric vehicles. He provides valuable information about the relations and power analysis of different stakeholders in the automotive market and the public policy impacts on electric vehicles.

3 Alejandro Sanz is the director of the group technology intelligence at SKF. He is expertise in technology megatrends/ road mapping and corporate strategy. He has a rich experience in automotive technology and market researches. He has published multiple papers in electric vehicle road mapping and supported many master graduates' theses. His research about the electric vehicle development pathway gives me a different view about the development pathway and actors' power towards the EV development. His broad knowledge in automotive market not only help me define and correct the morphological design but also stimulate my interests in broader researches in the longer range market and other technological innovation possibilities for the future automotive.

4 Jules-Joseph Van Schaftingen

JJ is the director in the Fuel Systems Architecture & Components Director at Inergy, which is a fuel system company. He has worked in Inergy for 22 years and he is a master expert in fuel system. My interview with JJ is more focused on the technological drawbacks and social challenges about the fuel cell vehicles' development, since he has wide knowledge in fuel cell field.

Through the interviews, I have firstly collected information to modify the morphological parameters and values, as illustrated in section 5; secondly explored the RS, in another word, the technological drawbacks and social challenges for each type of EVs' development. Besides, we also discussed the possible technological and business strategies to overcome these hurdles, which will be demonstrated in section 7.2.

6.2.2 RS of physical EV

The RS of physical EV are in two aspects: the technological RS and social RS. Technological RS refers to specific components or sub-system that hindering the technological performance of the EV system or prohibiting the diffusion of the EVS. Social RS indicate the main social issues towards the EV development.

6.2.2.1 RS of BEV

BEV includes four types of configurations in our research. In conclusion, BEV is a full electric vehicle which uses battery as the only energy storage system and electric motor to drive the wheels. BEV needs to be plugged in with outside power grid. The RS of BEV and the strategies to improve them are in four aspects:

1 The battery capacity, cost and battery life

The main challenge for BEVs comes from the energy storage system: the battery. The main issue is the battery's low energy density, heavy weight and high cost. All experts have the same opinions that the battery is the main RS of BEV. It can be explained in technological and social reasons.

From a technological perspective, battery is relatively low energy density compared to conventional gasoline tank which is a drawback of the performance of BEV system; however, this drawback does not constrain the usage of BEVs in urban areas as serve as it for the suburban or highway which requires longer range of driving demand. One expert pointed that the battery energy density cannot overpass the one of gasoline fuel due to the congenital drawback of battery. We do not know better ways to storage energy in a reasonable volume nowadays. It means BEV cannot beat ICV from a pure technological perspective. However, the environmental friendliness of BEVs makes it a more sustainable solution for future mobility. Besides, for urban mobility, we do not need a too big battery capacity. The big battery could only increase extra cost for the vehicle, but without real usage. One expert mentioned, to some extent, we do not want to improve the technology of battery, because the capacity for short range drive is already enough. Enlarging the capacity will only induce higher cost which is not welcomed by most customers. Hence, for urban mobility, most of the time, we do not need high capacity BEVs; however there are two factors which are influencing the situation now. First, people need occasional long distance driving such as going to IKEA or going to holiday. If they own only a short range BEV, they need extra driving alternatives. Second, we also need opportunity charging on the road, in the working places and commercial areas. In conclusion, for urban mobility, low energy density will still be a constraining problem for the BEV diffusions without opportunity charging available in public and alternatives for occasional long distance driving demand. In another word, battery energy density is technological RS now with the situation of no charging network and alternatives for long range driving requirements.

Step back from the energy density, from the social perspective, high cost of BEV is a big challenge for the BEV diffusion. The cost includes high upfront cost and extra replacement cost of the battery. The driving range of BEV today is maximal around 200 kilometres. For daily drive in urban areas, this range is far more enough; however the cost is still a significant issue. The battery price is around 600-700 dollars per kilowatt hour. And 60 to 70 per cent of the total cost of BEV comes from the battery. The high cost of the battery directly leads to high upfront cost of BEVs. High cost is still the main problem which is hindering the BEV's diffusion. Although the BEV realize complete tank to wheel zero CO_2 emission, which shows significant environmental benefits, however, incentive is far less decisive for customers to choose BEV. Majority customers still seem the cost as one of the most important criteria for car purchasing.

Many experts shows the opinions about how important the battery cost is, compare to the environmental achievements:

"As a matter of fact, what we expect people to be green? Everybody wants to be green as long as you don't touch his pocket. For majority of people, if the car costs 50-70% higher than the same model of ICE, they won't buy it."

To enhance the competitiveness of BEV, the cost of BEV should be at least compatible to the same mode of ICV. Some major technology observers predict the cost of battery could be between 200-300 per kilo watt power after mass production. Indeed the technological improvement of battery will decrease the cost dramatically as time goes.

Hence, the low power density and high cost really constraint the development of BEVs nowadays. One expert imagined that: "*if tomorrow there will be a fantastic technology improvement in battery. You will provide let's say power density times 5 than lithium ion, and the effective of cost half. It is completely changed.*" Actually the battery performance was doubled every two years. We can imagine that, maybe after five years, the BEVs will be affordable to the same level as ICVs. Hence, technological improvement is a way to correct the RS of low energy density and high upfront cost of BEVs.

Besides the battery cost, due to the low life time of battery, there is also an additional replacement cost of the battery which increases the overall cost of the BEVs. The battery may have four to five years' service life. The battery life depends on how much and how often it was being charged and how well it was taken care of. Therefore, if you charge the battery very quickly, the battery is usually destroyed very quickly. It is also one issue of DC fast charging that every time you charge the battery by DC fast charging, the battery life is reduced quickly. We will elaborate it in the next section about the RS of IEVs.

2 Safety and environmental benefits concerns of the batteries' components

From the social aspects, there might be a concern about the environmental pollution of abandoned batteries and potential dangerous of the battery substances. The components within the battery are usually very alkaline or acid. People may worry about the fluid and components when an accident happened. This could be a potential safety issue of using BEVs.

All experts agree that the most promising type of battery is lithium ion today and also in the near future. Lithium ion performance the best compare to other substances. Besides lithium-ion, the molten salt is also a bad substance for the environment. Polymer is probably quite safe. Lead acid is the cheapest, but the energy capacity is too low to become a reasonable battery.

3 Occasional range anxiety

Although for urban mobility, the average daily driving distance demand is relatively low as 40 kilometres per day, which can be reached by most BEVs today. So actually for urban mobility, the most applications are less than 100 kilometres. People do not need more than that daily. The normal BEV today can reach 100 kilometres by one fully charge. If plus the opportunity charging in public, the battery capacity is far more enough for urban driving demand.

However, people may have occasional requests for long distance driving during holidays. If there is no or not enough public charging stations along the road, it is impossible to take the BEV as a driving solution for holiday travelling vehicle. People will prefer a longer range vehicle such as ICV or HEVs. The occasional long distance driving demand is an important obstacle of BEV diffusion. This social RS is also induced by the technological RS that the battery's low energy density.

4 Global environmental concerns

Undoubtedly the BEV is a zero CO_2 emission from tank to wheel, it also provide much higher energy efficiency compared to ICVs, but is the electricity being used to charge BEVs cleanly produced? What is the efficiency level if we take the well to tank efficiency and CO_2 emission into account? Many have researched on the W2W efficiency of BEV, ICV and HEV.

However the efficiency results largely depends on the way of producing electricity. If the electricity is largely produced by coal-fired plants, the overall energy efficiency of BEV maybe much lower than that of ICVs. In that case, we cannot say BEV is a green vehicle. On the opposite, the use of BEV will bring us a worse global environment, because they will transfer the emission from urban areas to the power plant areas and further lead to a worse global environment. Maybe in some emerging countries, the production is still not being done in a clean way as it should be done. There are still a lot of coal-fired plants producing a lot of emissions nowadays.

Another concern from the vehicle customer side is the trust problem of all the green data being published and advertised for BEVs. People may feel that they are just displacing the problem from making it out of the exhaust pipe, but the pollution is being produced in the power plant. People who would like to own the BEVs may also care about overall societal benefit. From the societal perspective, there is a need to overcome the customers feeling that all the data of BEVs are propaganda. The perception need to be built up by giving them reliable, quantifiable data about the overall energy efficiently of BEVs.

6.2.1.2 RS of conventional HEV, plug-in HEV and range extended HEV

The benefit of HEVs is they can provide compatible driving range as ICVs. Hence, compare to BEVs, they do not have occasional range anxiety since people can easily use the current available gas stations to refuel the vehicles. In addition, the driving performance is enhanced by using EM to accelerate the vehicle. The usage of retrieving energy lost during braking by EM also increase the energy efficiency level of conventional ICVs. Hence, HEVs are more environmental friendly than ICVs.

The three types of vehicles have the same feature that they all partially use ICE as propulsion system or electricity generator, although they have different configurations and portion of battery usages; therefore they have mutual RS in terms of technological and social challenges.

1 High upfront cost and replacement cost

Similarly as the RS of BEV, HEVs also have the problem of high battery cost and replacement cost. Although the battery needed in HEVs are relatively smaller than it in BEVs, they still take extra cost on the battery besides the ICEs. The vehicle is even heavier than ICVs. The replacement cost of the battery is another burden to potential consumers. One expert mentioned that the battery usually takes extra space in the car, such as the trunk, which decreases the space for storage. It is also one drawback of current HEV designs.

2 Locally environmental pollution

All HEV still have the drawback of CO_2 emissions, although to some extent, they more or less decrease the level of CO_2 emissions of ICVs which will keep deteriorating the local environment. This results from the technological design configuration of HEVs and also from social customer usage habits.

From the technological design perspective, all the HEV types include the dirty system of ICE. They will continue producing CO_2 emissions as long as they are being used. Indeed plug-in HEV and range extended HEV provide us opportunities to achieve zero emission vehicles during low speed drive and within the battery depleting range. However, do the technologies of HEVs really contribute to the environment as we expected?

Many experts argue that, from the social perspective, most customers' driving habit are still using the alternative ICE instead of charging the battery and using pure EM to power the wheel. This using habit is shaped by multiple social influencing factors including the unavailability of charging stations, long time level 1 charging at home, and lacking incentives to charge the battery in the working places. HEVs do not have the infrastructure problem, compared to BEVs on the grounds that they can use gas stations to refuel the tank. Therefore, there is a dilemma between charging the batteries to contribute more to the local environment and just refuelling the tank by using accessible gas stations.

One expert gave an example of the significant social drawback of extended range HEVs as lacking of appropriate company incentives or business models to encourage using the batteries :"I am wondering how many people actually plug in there at night in their house. Because you always have gasoline engine to charge the battery, the question is does it need to charge it even. So yes, a lot of options are available, are they really being used. Because if you take the company car as example, let's say I have a company car. my company pays for the fuel, but they may not pay for the electricity. So what is the incentive for me to take the vehicle and plug it into my house at night. There is almost no. So that's the kind of the company incentives, the government incentives and the fleet ownership, how does that work, how does that business model work. " Therefore, in the future, a comprehensive incentive mechanism is in demand to fully encourage the usage of batteries in the HEVs.

Conventional HEVs are vehicles which only use the battery and electric motor in the use of providing starting propulsion, and capture the energy during braking to the battery. Conventional HEVs do not need charging stations to provide external energy. The battery being used is usually small capacity. This type of vehicle can improve the energy efficiency by retrieving the energy lost from braking and provide more efficient starting and accelerating power than ICVs. By efficiently using the energy, they can lower the emission level.

Similarly as the BEVs, the RS of this type of HEV also comes from the battery. Extra battery takes more space than conventional ICVs. This will decrease the available space for the storage. The cost is also a problem for conventional BEVs. The high upfront cost and replacement cost of the battery are also challenges for this type of vehicles.

Besides, since battery is only used as ancillary propulsion energy storage, the ICE is still producing large amount of pollutions to the air. This type of vehicle doesn't provide opportunity to green usage of energy.

6.2.1.3 RS of FCEV and fuel cell hybrid vehicles

Compare to BEV or HEVs, FCEV and fuel cell hybrid vehicles are laggard in terms of market penetration. There are no FCEVs or fuel cell hybrid available in the market nowadays. However from the technological performance perspective, FCEVs can achieve longer range compared to BEVs. Through the interviews, we concluded main RS of FCEVs and fuel cell hybrid vehicles in two perspectives:

1 Replacement cost of membrane and components within the fuel cell

Since there are chemical reactions within the fuel cell stack, after the membrane is used up, it need to be replaced. The membrane replacement could be very costly, similarly as replacing a battery.

2 Safety issue

The safety issue of FCEV and fuel cell HVs results from both technological and social reasons.

From technological perspective, FCEV is dangerous because of two reasons: the fuel being used is easily explosive and the hydrogen storage difficulties. In order to keep the technology safe, additional protection technologies are needed, such as cooling system. The technology is available to provide the safety fuel cell stack for vehicle as safety as current gasoline vehicles, however there is a dilemma between the safety level and the cost of providing the protection technologies. Hence, from technological perspective, the technology is mature enough to guarantee an acceptable safety level for FCEVs, but the drawback of it is high cost. It depends on at what cost can we reach the acceptance safety level, and at what cost customer would like to pay for this type of vehicles. Beside the dangerous of hydrogen itself, the process of transferring hydrogen from the tank of storage facility to one's car is also seemed very risky.

From social perspective, people may have the image that hydrogen vehicles are more explosive than gasoline cars. One expert describe it as "sitting on a hydrogen bomb", another mentioned that "seldom people would like to see their family sitting in a FCEVs nowadays, even if the technology is available." Since we have no experiences of using hydrogen vehicles, we really need time to proof the safety of FCEVs. Even if one day when the technology of FCEVs are cost-effective, but if the market still have the perception that FCEVs are dangerous, then it is not profitable for the industry. Hence, the technology if feasible, there is no blocking point in the technological availability, the safety issue in terms of cost-effective and social perception are the main challenges for FCEVs and fuel cell HVs to overcome.

3Lacking of Infrastructures

The infrastructure for fuel cell is still niche with only a few demonstration projects in California. Lacking of refuelling infrastructure is a big hurdle for the FCEV diffusion. Not like BEVs that electricity is easier to get at home and there are also many charging spots available in many countries, the infrastructures for FCEV is unavailable both at home and public. The hydrogen refuelling is both dangerous and expensive to attain. It is a chicken and egg problem that without a network of refuelling stations, no one would buy the FCEVs. Without having FCEVs on the road, no private sectors would like to invest in refuelling stations, either. In order to achieve the diffusion of FCEVs, a network of hydrogen refuelling stations need to be installed. We will talk about the RS of hydrogen refuelling stations in section 6.2.3.

4 Global environmental concerns

From the tank to wheel perspective, FCEV is extremely environmental friendly. However, the way of producing hydrogen is not necessary an environmentally friendly process. The process of producing hydrogen need both a lot of electricity and a lot of chemicals in order to be able to produce the hydrogen to be used in the fuel cell. The total station to wheel emission level maybe contributes more pollution to the global environment. We will elaborate it in section 6.2.3.

6.2.1.4 RS of SCVs and super capacitor hybrid vehicles

The RS of SCVs and super capacitor HVs are: firstly from technological perspective, super capacitor today is still low energy density solution. It has similar technology concerns as battery, such as high cost and low capacity and short life span. One expert mentioned that it is difficult to use super capacitor to drive the vehicle, but there could be the combination of super capacitor with other energy storage systems, such as flywheel.

6.2.1.5 RS of flywheel vehicles and flywheel hybrid vehicles

Different from BEVs or HEVs, the main RS of flywheel vehicles are from the technological reasons and their induced safety concerns. One technological barrier need to be gone through is the system need to be lubricated very well in order to decrease friction. It also works in vacuum. Any short clotting within the system will surely reduce the life of flywheel and reduce the performance overtime and also cause catastrophes. Usually the flywheel system runs in 60 to 70 thousands RPM (revolutions per minute). If the system fails, the result will be catastrophic. Therefore flywheel needs to be very heavy and needs many metals around it to make it safe and protected.

Second technological barrier comes from the mechanical reliability. The component of flywheel is running in a very high speed which can affect the vehicle dynamics that the vehicle may tend to do strange things. One expert gave an example to describe the potential strange driving experience of flywheel vehicles: *"In the old cars, you have an old inline engine. It is driving the back wheels. When you put your foot on the gas and accelerate, the car moves a little bit to the side, it rolls a little bit. If you have such an high energy it can slow down and speed up. It would be a strange driving experience to the users."* This also induced both the safety concerns and driving performance problems. Hence, the RS of flywheel vehicles are mainly pure technical aspects. One expert expressed that this type of vehicle is probably the least market acceptable toady.

There are too many technical hurdles which are preventing flywheel from being a main stream energy technology today. The technological RS make flywheel vehicle destined hopeless in the market. More than that, from the social perspective, the additional cost for the component in flywheel is also a RS for the flywheel vehicle diffusion. The working principle of flywheel is using wheels to charge the flywheel and take the energy from flywheel when it is needed. In order to achieve this, an additional system is needed, and that will add extra cost to the flywheel vehicle.

6.2.3 RS of IEVs

The RS of IEVs are discussed separately in charging station which includes level1, level 2 and DC fast charging stations, battery swapping station and hydrogen refuelling station.

6.2.3.1 RS of charging stations

There are already several options for charging stations nowadays. EV owners can charge it at home, in public parking lots or commercial parking places, etc. There are also many charging solutions, such as inductive or conductive charging and fast charging or low charging. We will illustrate the RS of each type of charging solution separately.

1 level 1 charging station

Level 1 charging is installed at home garage or apartment parking places. This solution allows people to fully charge their vehicles during night at home. There is no blocking point of this type of charging since 12 hours charging could be meet by most customers. The only concern may be the impacts to the power grid at night, if so many vehicles are being charged during the same period.

2 level 2 charging station

Level 2 charging takes shorter time than level 1, it usually requires 5-6 hours to fully charge the battery. Since during most of the time, people are parking their vehicles, this solution provides people opportunity charging during day time at work, in a shopping centre, etc. There are two options for this type of charging: inductive and conductive charging. The inductive charging is preferred by all experts. All experts showed strong interests and affection towards this solution. The technology is absolutely available, just like an inductive toothbrush charger. However, the main RS remaining in this type of charging station is energy lose during charging, because you have to make the charging place very close to each other in order to optimum efficiency. The challenge here is to provide infrastructure which is able to get close enough to the charging point of your car to be able to transfer energy in an efficient way.

3 DC fast charging station

DC fast charging provides opportunities to charge the vehicles in a very short time around 30 minutes. The technology standard has been developed in Japan named “CHAdeMO”, which is an abbreviation of “would you like a cup of tea?” in Japanese. The technology provides quick charging opportunity which can fully charge a battery within a tea time.

The main challenge today for DC fast charging is a technological difficulty that this solution will reduce battery life dramatically. The battery will be destroyed very quickly when a lot of energy is put so fast in a battery. By having DC fast charging, there are techniques to make it work better or less better, but at the end of day, with today’s technology, every time the battery is being charged in DC fast charging device, the battery life is being reduced.

Another discuss towards DC fast charging is that is it necessary to provide DC fast charging in urban areas? Since most of the time, most urban vehicles are parking rather than being driven on the road, this charging option seems unnecessary for short distance drive. But for long distance cursing such as the highway driving, DC fast charging is one of the best solutions for BEVs.

6.2.3.2 RS of swapping stations

After the bankruptcy of the “Better Place”, which is the first and the only battery swapping station, there is no available battery swapping stations in the market now. The RS of battery swapping station is logistics about the allocation of batteries in different locations and matching the type of batteries with different types of vehicles. One expert gave a vivid example of possible difficulties of battery swapping logistic problems:

“If I go to a garage, and I turn up and say, I have my Toyota Prius, the guy said:“ I’m afraid we only got Volt batteries.” That’s not so convenient. So you need to know that along the road I am taking, am I sure the garage I am going to stop by, am I going to be sure that they have the same battery I need. Here is more about the logistics rather than the infrastructure for it.”

The logistic of battery swapping stations need to build up a network to move the batteries around. They need to be able to delivery and redistribute all the batteries. Imagine if all the batteries started at Detroit, and they ended in Chicago, then there are no batteries in Detroit any more. So it is about the logistics management about how to allocate the batteries according to customers’ demand.

6.2.3.3 RS of hydrogen refuelling stations

The hydrogen refuelling station is very niche with only one demonstration project in California nowadays. Some countries have significant actions towards the building of hydrogen refuelling stations, such as Germany which has planned to install in 2030. But until now, hydrogen refuelling stations are still unavailable to public. The main RS of hydrogen refuelling station are safety issues, environmental concerns and high cost of production.

1 Safety issues of hydrogen production, transportation and storage

There are normally two types of hydrogen refuelling stations: on-site hydrogen production station and off-site hydrogen production station. For the offsite hydrogen producing, hydrogen will be produced from remote plants and transported the high pressured gas to refuelling stations. In order to get enough hydrogen, the hydrogen needs to be compressed down to a very small volume. The challenge of offsite hydrogen producing is how to handle the amount of pressure safely and effectively refuel refuelling stations.

2 Cost-effectiveness of hydrogen production and transportation

For on-site producing stations, there may be no safety issues related to hydrogen transportation. But the cost-effective of investment is one challenge for this type of stations. The design of hydrogen stations needs to balance the transportation cost with the infrastructure investment that needed in this location. Hydrogen production is expensive, and if we need to provide on-site producing stations in a densely populated area, the investment will be significant. One expert provided a scenario of the allocation of the two types of infrastructures:

"The investment for on-site refuelling stations may be cost-effective when you have very big distance in between. Let us talk in the US, when you want to go from the east coast to the west coast, and you may need three refuelling stations along the point, which is not so smart to transport hydrogen from all the way along this road, and drop away at each location. It is better if each of these locations is able to produce its own. But when I get to the other land, when I mean, let's say California or the Carolinas, where the population is denser. There would be more stations tend to be designed as off-site types, because there will be a lot of investments for hydrogen production. The pure capital investment for this will be significant."

Therefore, due to the high cost of hydrogen production, storage and transportation, the cost-effectiveness of station network design is a significant issue for the development of hydrogen refuelling stations. Again as illustrated before, the network needs to be built based on the fact that there is enough demand of FCEVs. Without this condition, no private sectors would take the risk to invest huge capitals into hydrogen refuelling stations.

3 Global environmental concerns

The production of hydrogen needs a lot of electricity, the way how the electricity is being produced decide how clean and how energy efficient the entire fuel cell vehicle system is.

6.2.4 Additional concerns about the EV future

If you look at the infrastructure of today, mostly if you talk about long distance travel, it is going to be the hybrid type. We talked about the electric hybrids, which are running on a more traditional fuel today. FC hybrid still has a long way away. From a technological point of view, not only because of the infrastructure, but there is still a gap in the technology to be able to have enough range, maybe being able to safely store, execute the hydrogen and have enough life of the fuel cell. If you look at trends now we have in shale gas, there will be more trends towards LPG type solutions, when we are using gas to power engines. Again we come back to the hybrid solution, you have the parallel and series hybrid, I don't see any more.

6.3 Results confrontation and validation

As explained earlier in section 1, the methodology of this research is a combination of morphological analysis and reverse salient to explore the RS of EV system in order to explore strategies to overcome the drawbacks. In this section, we confront the RS acquired from morphological analysis and expert interviews with the results from previous literatures. As shown in Figure 6.3, we can seem the process as a confrontation of two research pathways: first, to explore RS from reviewing scientific papers and industry reports; second, to find out RS by consulting experts based on the results of implementing morphological analysis. In this section, we will confront the results from the two pathways in order to validate the results. We will draw a conclusion of RS for EV system then further explore strategies to overcome the RS in the conclusion section.

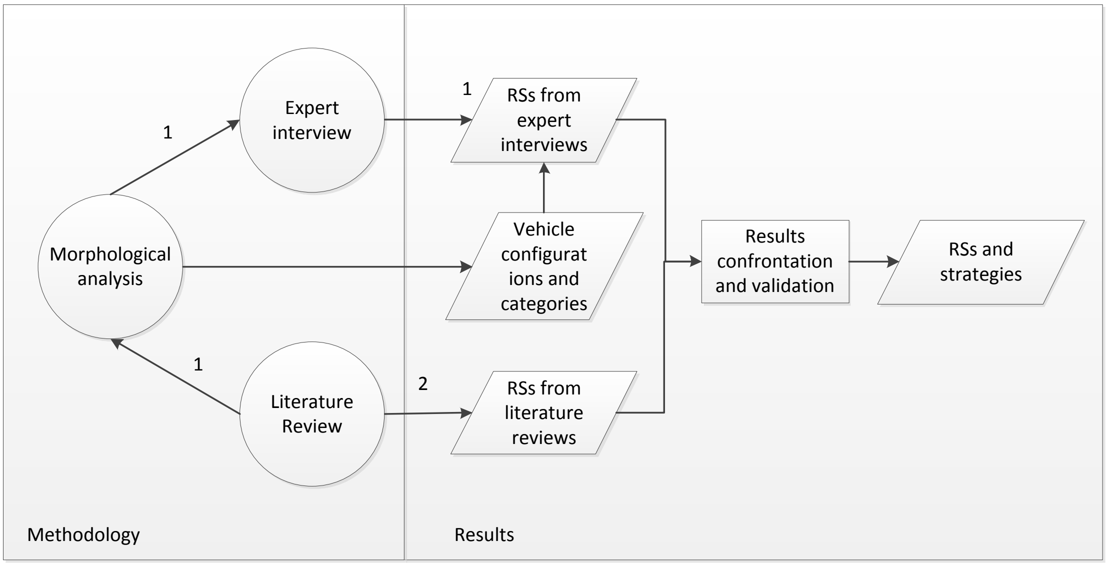


Figure 6.3 Methodology and results diagram

6.3.1 Similarities and differences

Most conclusions about the RS of EVs are the same from both pathways. Both literature review and expert interviews based on morphological analysis results have generated some mutual conclusions. There are also some deviations between the two results. The RS results from both pathways are concluded in addendum III: RS of EV for urban mobility. This form clearly shows the mutual results from both pathways. We will not repeat them again, but we want to discuss the differences between the two results. The differences also leads to some interesting debatable questions which can be researched on in the future research.

1 The well to wheel energy efficiency of BEV, HEVs and FCEVs

According to literatures reviews, most papers seem the usage of BEVs; HEVs and FCEVs can provide higher energy efficiency than comparable ICVs. Many research results show the detailed efficiency level of all the options, and proofed that even if the EVs are charging to dirty electricity which is produced by coal-fired plants, the overall CO_2 emissions from well to wheel is still lower than ICVs. Only one recent study from (Associates, 2013) reveals the possibility of negative environmental impacts from using EVs.

However, all the interviewees reflect that it is hard to compare the well to wheel CO_2 emissions among BEVs, HEVS, FCEVs and ICVs. They also doubt the reliability of the current data from reports. If the electricity being used to charge the battery or produce hydrogen for the fuel cell is produced by coal-fired plants, then the overall CO_2 emission may be much higher than ICVs. Coal-fired plants are still taking a large portion of total electricity productions globally. The green production such as using renewable power of wind power, tide power and solar power generation are still inadequate in the mid-east countries, some fast developing countries like China and Indian, and some western countries.

The action of large diffusion of EVs may negatively impact on the global environment by producing more GHG emissions. The option of EVs cannot solve the inherent problem of air pollution, but just transferring the problem from local to global environment. Therefore is the EV development really benefits to the global environment is a debatable question. The answer closely depends on the way of electricity producing in a country or a city.

2 The necessity of pushing EVs into the automotive market

No literatures have discussed the question if we should really focus on EV development and invest large amount of capitals to support EV diffusion by assisting technology innovation and constructing infrastructure networks. But some experts doubted but not disapprove the necessarily of pushing EV technology into the market based on three reasons.

Initially, as described above, the large diffusion of EVs may result in a worse situation for the global environment due to the dirty electricity production method. Besides, not only the EV technologies are improving, but also the traditional ICVs technologies are improving towards a more energy efficiency and cleaner vehicles; so there is a high chance that ICVs can achieve a higher energy efficiency than EVs, especially under the condition that the electricity being used for EVs are not cleanly produced. At last, but not the least, the economic-effective of the large adoption of EVs closely depends on real-time oil price. One of the most important reasons for pushing EVs in many countries is trying to lessen their dependence on oil. However, the large exploration of natural gas in recent years may change the situation of expected depleting oil reserves and will decrease the oil price dramatically in the future.

Hence, if all the above situations will occur in the near future, not changing to electrification transportation would be a better choice for economic-effective objective and global environmental benefits.

3 Lack of incentives of charging vehicle batteries

If we only consider the tank to wheel energy efficiency or CO_2 emissions, HEVs perform better than ICVs. The design of plug-in HEVs is expected to reduce CO2 emissions produced by combusting gasoline by providing opportunities to charge the vehicle battery. Most literatures did not pay attention to the charging preferences of PHEV and EREVs' charging preferences. Only (Graham, 2001) shows that customers prefer to plug in HEVs instead of refuelling gasoline, based on PHEV customer interviews.

However, the results from expert interviews show the opposite conclusion. Experts doubt about the real charging frequencies of PHEVs and EREVs since these designs also allow using refuelling gasoline to either power the wheel or charge the battery. Due to lack of charging infrastructures in public, employers and commercial parking lots, customers would tend to just refuelling the gas tank by using existing gas stations rather than looking for a charging spot. Although various incentives have been given to the HEV purchasing, there still lacks of incentives to encourage HEV users to charge the vehicle batteries. For instance, if an employee is using a company owned HEV, and no charging facilities are provided in the company. He or she would prefer refuelling the vehicle by spending the company's money rather than charging it at home during night by spending his own electricity fee.

4 Occasional range anxiety for urban mobility

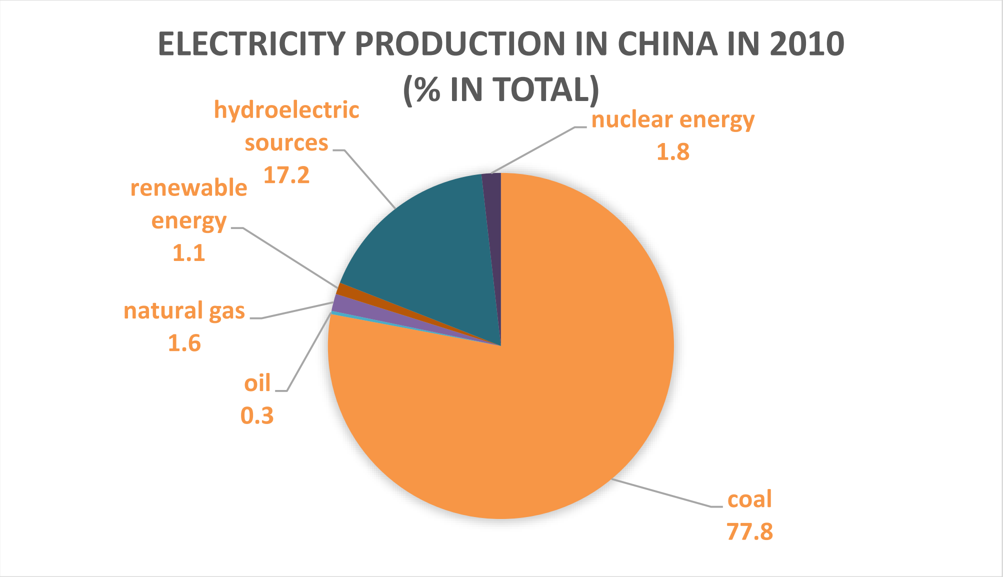
Since most literatures did not constraint the research boundary as urban mobility, and our interview was conducted within the boundary of only considering short distance mobility, we have more targeted findings toward the demand in urban areas. Many experts stated that urban citizens not only need basic daily driving, but also require occasional long distance driving. The current BEV range is far enough for provide this requirements, therefore how to meet the occasional range anxiety is also a RS for BEV adoption.

7 The RS of electric vehicle system in China

In this section, we will discuss the main RS of electric vehicle system in a specific country, China. The important information of electricity production methods in China and China's policies about the development of EV are analyzed to find out the main RS. Based on that, further strategies are suggested to the China's central government for a better encouragement and deployment of the electric vehicle system in China in the conclusion and recommendation section.

7.1 Background of China's electricity production and oil dependence

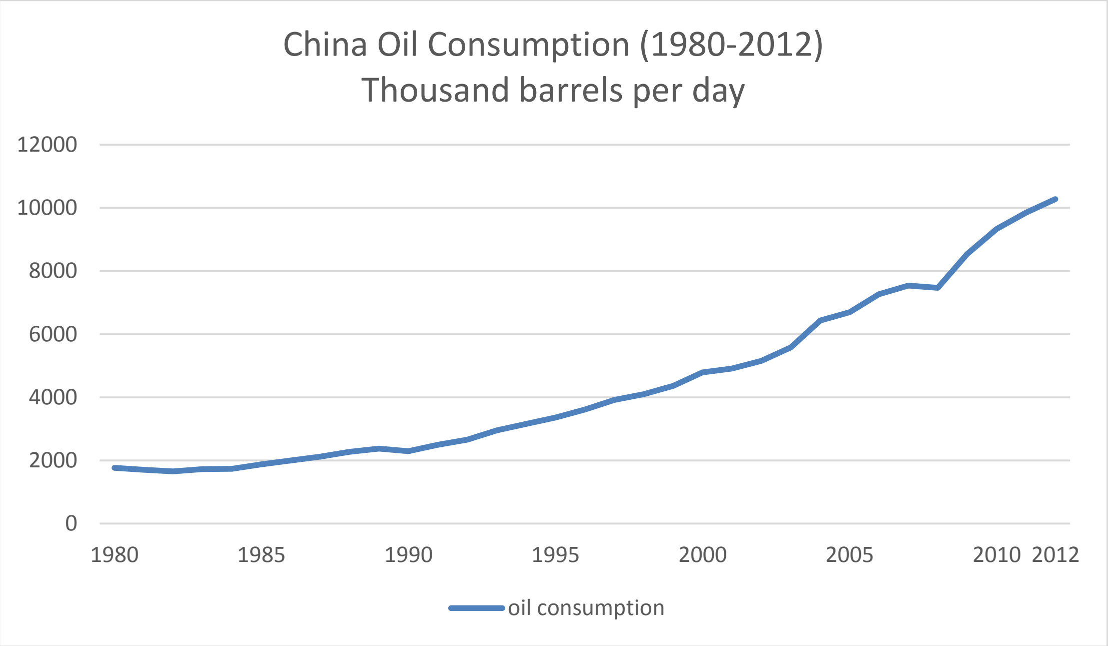
As shown by the data from 2010, the total electricity production in China was 4,208 GWh. Among which, 77.8% of electricity is produced from coal sources, which generate a large amount of CO_2 emissions. The coal consumption in China was the largest in the world, which accounts for almost half of the world's coal consumption ("Country analysis brief overview," 2012). Nuclear power, hydroelectric and renewable energy are relatively much cleaner than coal sources, which do not release or release relatively less GHG emissions during the production of electricity. Among all the low CO_2 emission energy sources, hydroelectric energy sources have been used the most, which takes 17.2% of the total energy sources. These hydroelectric sources come from the famous Three Gorges Dam, Gezhouba Hydropower Station, Xiaolangdi Hydropower Station, Xin'anjiang Reservoir and Danjiangkou Reservoir. Besides, nuclear power takes 1.1%; renewable energy sources take 1.8%. Hence, the total green energy sources being used for electric generation is 20.1% of the total energy sources.



Data source: ("Electricity production," 2013)

According to the data from Energy Information Administration (EIA), China is the second-largest consumer of oil after the US in the world now ("Country analysis brief overview," 2012). The diagram shows the daily oil consumption in China from 1980 to 2012. The dependence on foreign oil in China was growing as the increase of oil demand. The oil dependence on import were 42.9%, 47%, 50.5%, 51.3%, 53%, 53.8% and 56.7% from 2005 until 2012. Undoubtedly, EVs are welcomed by China's government since it will help to decrease China's dependence on oil.

Diagram 7.1 China Oil Consumption (1980-2012)



Data source: ("Country analysis brief overview," 2012)

7.2 Government policies towards the development of EV

The sale of vehicles in China has been top 1 in the world for four years from 2009 until now. The sale was more than 19 million units on 2012. Many have predicted that the demand will keep increasing dramatically in the coming years.

By July, 2007, the Ministry of Technology announced a plan, "the National Twelfth Five Year Plan about Scientific and Technology Development", which claimed that the EV sale is planned to reach 1 million by 2015. Besides, 400,000 charging piles and 2,000 charging and swapping stations will be installed in the 20 demonstration cities by 2015 to meet the demand of EV charging. In the following years, to encourage the EV diffusion to the market, Chinese central government has launched a series of demonstration projects and certain incentive policies to EV customers and EV industries. All the national projects about EVs and their corresponding policy incentives have been listed in the Form 7.2(a).

Form 7.2(a) EV Projects and Policy Incentives in China (2006-2013)

Policy title and date	Main contents	Subsidy conditions
“Ten cities, one thousand” Project.(2009-2012.12)	Aim to launch demonstration projects of EVs in 10 new cities every year, and launch 1000 vehicle for each city. There are 13 cities in 2009, 7 cities in 2010 and 5 cities in 2011 which are involved in the trail project. Beijing city is in the first trail group. The total EV number is expected to reach 10% of the total market sale in 2012. The policy includes subsidies for the purchase of public transportation services(bus, taxi, official car, sanitation trucks and postal vehicles).	1 Within the provision of vehicle models. 2 the oil saving rate of passenger cars and light commercial cars should be at least 5% higher than comparable ICVs; the oil saving rate of bus should be at least 10% higher than comparable ICVs. 3 the battery and other key components should have at least 3 years life span (150,000km)
“The announcement of subsidies for private purchase of energy vehicles” (2010.5.31-2012.12)	Five cities are selected to take the subsidy benefits of EV purchase, EV leasing and battery leasing. The five cities are Shanghai, Hefei, Shenzhen, Hangzhou, Changchun. The policy provides subsidies of 3000	1 within the EV menu 2 BEV’s battery energy should be higher than 15 kW; PHEV’s battery energy should be higher than 10 kWh (50 km driving range under pure electric mode) 3 Vehicle production companies and key components producers should have a certain production scale and service system. They should guarantee at least five years or 100 thousand maintenance services. They should commitment recycle the whole vehicle and

	RMB/kWh which means maximum 60,000 RMB subsidies for BEV purchase and maximum 50,000 RMB for PHEV purchase. The subsidies will be decreased when the total amount of sale reaches 50,000 units.	battery by a certain depreciation rate. 4 Auto companies should provide product performance parameters according to the national standards: the top speed of BEVs in 30 minutes, the top speed of PHEV; acceleration time for 0-50 km/hour; maximum grade ability ; driving range; motor type, etc.
“The expansion of new energy vehicles demonstration cities”(2012.8.6)	Expand the policy applicable cities from the current 25 cities from “Ten cities, thousand vehicles” project to all the cities in China.	
“Financial incentives to technology innovation projects for automotive industry” (2012.9.20)	Financial incentives to the automotive companies which have: Projects about either the whole vehicle technology of BEVs, PHEVs or FCVs or battery technology. 25 projects were selected in 2012 which includes 5 projects of pure electric buses; 5projects of plug-in electric buses; 3 projects of commercial BEVs; 3 projects of commercial PHEVs; 1 FCV project; and 8 projects of battery technology.	Maximum speed of passenger BEVs>=100km/hour; the maximum speed of plug-in electric buses>=80km/hour; the maximum driving range under the usage of battery of plug-in electric buses >=50 km; All vehicles must be installed remote vehicle diagnosis system for monitoring of information security status.

Data collected from (*Financial incentives to technology innovation projects for automotive industry*, 2012; *List of projects to be supported in the 2012 new energy vehicle technology projects*, 2012; *The announcement of energy conservation and new energy* *vehicle demonstration projects*, 2009; *The announcement of subsidies for private purchase of energy vehicles*, 2010; *The announcement of the expansion of public services, energy-saving and new energy vehicle demonstration projects*, 2010; *The expansion of new energy buses demonstration cities*, 2012)

There are generally two types of demonstration projects in China: project about public purchase of EVs and projects about private purchase of EVs. Chinese EV policies are more inclined to the public EV purchase projects rather than to the private EV purchase projects in the previous 5 years. "Ten cities, thousands vehicles" project oriented for public purchase of EVs. It started from 2009. Several follow-up policies have been raised about the public purchase of EVs, and the scope of applicable cities was enlarged from the initial 13 cities in 2009; 7 cities in 2010; and 5 cities in 2011 to all the cities in China by 2012, as shown in form 7.2(b). On the other hand, the personal purchase policy started relatively later than public purchase one on 2010. The demonstration cities are limited to five cities which is also less than the scope of public purchase project. Besides, the private purchase project only lasted for two years. It was terminated by the end of 2012. After the termination of this policy, personal purchase of EV is also shelved. Until now, no new private purchase projects or policies have been officially issued in China.

Form 7.2(b) Demonstration City list of the "Ten cities, thousands vehicles" Project

Project Phase	Involved Cities
Phase 1: start from 2009 until now	Beijing, Shanghai, Chongqing, Changchun, Dalian, Hangzhou, Jinan, Wuhan, Shenzhen, Hefei, Changsha, Kunming, Nanchang
Phase 2 :start from 2010 until now	Tianjin, Haikou, Hangzhou, Xiamen, Suzhou, Tangshan, Guangzhou
Phase 3: start from 2011 now	Shenyang, Chengdu, Hohhot, Nantong, Xiangfan
Phase 4: start from 2012 until now	All other cities in China

Data sources: (*Financial incentives to technology innovation projects for automotive industry*, 2012; *List of projects to be supported in the 2012 new energy vehicle technology projects*, 2012; *The announcement of energy conservation and new energy vehicle demonstration projects*, 2009; *The announcement of subsidies for private purchase of energy vehicles*, 2010; *The announcement of the expansion of public services, energy-saving and new energy vehicle demonstration projects*, 2010; *The expansion of new energy buses demonstration cities*, 2012)

The incentive subsidies for public services EVs are from 28,000 RMB to 600,000 RMB based on the requirements of different EV types, as shown in the Form 7.2(c). The subsidies for private purchase of BEV and PHEV are 60,000 RMB and 50,000 RMB respectively. These subsidies were directly given to the EV production companies in order to reduce the price of EVs. However, even after the subsidies, the prices of EVs are still higher than the prices of comparable type of ICVs.

Form 7.2(c) Subsidy standards for public service passenger cars and light commercial vehicles within the demonstration

（Unit：10,000 RMB/unit）

Energy-saving and new EV type	Oil saving rate	Maximum electric power ratio			
		BSG	10%-20%	20%-30%	30%-100%
HEV	5%-10%	0.4	——	——	——
	10%-20%		2.8	3.2	——
	20%-30%	——	3.2	3.6	4.2
	30%-40%	——	——	4.2	4.5
	>=40%	——	——	——	5.0
BEV	100%	——	——	——	6.0
FCV	100%	——	——	——	25.0

Note：The subsidy standards of maximum electric power ratio which are higher than 30% include PHEV

Data source: (*The announcement of energy conservation and new energy vehicle demonstration projects*, 2009)

Form　The subsidy standards for buses longer than ten meters

（Unit：10,000 RMB/unit）

Energy-saving and new EV type	Oil saving rate	Lead-acid battery system	nickel-metal, lithium-ion battery / super capacitor hybrid system	
			Maximum electric power ratio 20%-50%	Maximum electric power ratio >50%

HEV	10%-20%	5	20	——
	20%-30%	7	25	30
	30%-40%	8	30	36
	40%以上	——	35	42
BEV	100%	——	——	50
FCV	100%	——	——	60

Note：The subsidy standards of maximum electric power ratio which are higher than 50% include PHEV

Data source: (*The announcement of energy conservation and new energy vehicle demonstration projects*, 2009)

The current policies are also more inclined to BEVs rather than PHEVs for electric buses. Besides, FCEV did not receive as much attention as BEV or PHEV did. First, the subsidies to BEVs are higher than the subsidies to PHEVs in both public and private purchase of EV projects. Second, among the list of the financially supported projects, as shown in Addendum IV, although according to the title of project type, BEVs and PHEVs were given equal opportunities of subsidies; but if review carefully to the project name, we will find that among plug-in electric buses projects, project 14, 15 and 16 are about or partially about technology innovation of pure electric buses.

7.3 Policy Results

The total investment was accumulated about 6.95 billion RMB until now. However, the sale results are not as optimistic as planned. Published broadly by the media in China, until March, 2013, there are only 39,800 EVs on the road in China, in which, 80% are used in public transportation (Xueqing, 2013). Among the sold EVs, BEVs take a bigger amount than PHEVs. During the first half year of 2013, there are in total 5,889 EVs being sold, in which 5,114 are BEVs and 775 are PHEVs. The whole sale accounts for 0.05% of the total new car sales in China (Xueqing, 2013). The data collected from other sources claimed that, by 2012, China holds the stock of 11,573 EVs which accounts for 6.2 % of the global market. The sale data directly reflected the results of China’s previous policies towards EV development. There are more BEVs than PHEVs in the market; besides, public EVs take more than 80% of the total EV market.

Clearly, China cannot reach the original plan made by 2006 that reaching 1 million sales of EVs by 2015, according to the current diffusion rate of EVs and production ability of EV production companies. By June, 2012, another important plan of EV development was announced by the state council of China. In the report named “The notice of the issuance of new energy automotive industry development plan (2012-2020) by State Council, a new plan of EV sales was changed to 500,000 by 2015; the production capacity and sale of EV are planned to reach 2 million by 2020; the technology and market of FCV should reach the same level as international FCV development. Based on the current EV sale data, this plan is seemed hard to realize, either.

The related charging infrastructures for EVs have been installed in the 25 demonstration cities. State Grid, CPCC, CNOOC, China Southern Power Grid and CNPC, and other state owned enterprises are in charge of the installation of charging stations. State Grid is the main body of building charging stations. By the end of 2011, the State Grid of China has installed 243 charging stations and 13283 charging piles. The total charging stations and charging piles were 314 and 16184 in 2011. By the end of 2012, there are 800 slow charging stations in China and no fast charging stations or swapping stations have been installed("Global EV Outlook 2013-Understanding the Electric Vehicle Landscape to 2020," 2013). Most charging infrastructures were installed for buses or government usage EVs. The installation services for personal charging device have not been started in most cities. For instance, in Beijing, since no private installation services have been opened, EV users could not install charging devices at home. The Shanghai city just started the personal installation service with the technology provision by the State Grid of China on May, 2012 when there are 269 personal EVs in the market. From the national level, no policy incentives have been issued to personal charging devices’ installation.

The business model of car leasing started relatively late in China too. The first EV leasing business model just started on June, 2013 in Shanghai by the car leasing company, eHi Car Service. There are 50 EVs and 3 services points in Shanghai. The daily rental fee is 149-151 RMB/day from Friday to Sunday and 75-77 RMB/day from Monday to Thursday. Other EV car leasing companies are expected to appear soon.

In summary, there is still a long way to go for China to reach the goals. Besides, lessons should be learnt from the previous demonstration projects; new policies are in demand to stimulate the market not only in public services purchase areas, but also in private purchase areas. In the following contents, we are going to analyze the RS in China’s EV market. Based on the results, new policy suggestions will be made.

7.4 RS of the development of EV in China

By the definition of RS, there are generally two types of RS for large scale technological systems: technical drawback which is hindering the technological performance of the entire system; and social barriers which are blocking the market acceptance and success of the technology system. In China, the development of EV system is facing both technological hurdles and social barriers. Currently, the social RS is mainly blocking the performance of EV system more than the technological RS. We will demonstrate the RS of EV system from both technological and social perspectives and explain the reasons why social RS has a stronger negative impact on the EV system rather than technological RS.

From the technical side, the technological RS of EV system in China is from the high production cost of the battery which leads to the costly of the whole EV. The high production cost of the battery results from the expensive raw material and low production rate. The current performance of available EV types in China, such as the driving range and maximum driving speed, can totally meet the demand of urban drive in China. Especially for the highly congested and polluted cities like Beijing and Shanghai, which do not need high speed of driving demand and at the same time urgently require decreasing urban vehicle emissions, the current EV technology is qualified in terms of driving performance.

The EV market in China also share the economic RS as the high cost of the battery. As concluded before, high cost of the battery is a universal problem nowadays around the world; which means in order to push the EV into the market, government regulation is necessary. Without government regulation of policy preferences to EVs, EVs cannot enter to the current automobile market. Because of the high cost of the vehicle, lacking charging infrastructures and other problems, in a free market of EV system, on one side, consumers will tend to choose cheaper ICVs; on the other side, EV manufacturers will hesitate to research and develop EVs or launch the unprofitable products into the market. Therefore, government intervention plays a key role in the initial phase of the development of EV system.

The current poor performance of EV diffusion in China is more impacted by social factors, such as government policies, consumer cultures and EV market position and diversity than pure technical hurdles. In China, since all the main technological system are highly regulated by the central government, the business decision and strategies of automobile manufactures and charging infrastructures providers are highly impacted by the public policies. Without government policy of obviously supporting EV market, no stakeholder would take the risk of investing a large amount of money into the EV market. Some successful cases from other countries like the US, Denmark and Japan proofed that government regulation have the ability to stimulate EV diffusion effectively.

7.4.1 RS of government policies

It is the macro public policy background of China decided the depression of the EV market today. The disadvantage of China's previous policy towards EV development could be summarized into three perspectives: strong policy biases; policy delay and discontinuity; and local protectionism.

First, there are strong policy biases in China's previous EV policies. The policies are inclined to boost public usage than private usage of EVs; to encourage the purchase of BEV than PHEV for electric buses; to provide purchase subsidies in limited cities rather than nationwide; to give subsidies only to limited domestic EV brands rather than all qualified EV brands including foreign ones.

The inclination to public EVs can be shown in three aspects: first, the demonstration project of the public purchase of EVs are issued one year earlier than the demonstration of private purchase project. Second, The policy of EV purchase incentives have been extended to all the cities in China by the end of 2012; however no following policies have not issued to extend the policy of private purchase subsidies. Third, there are no services available for personal installation of charging piles. On the opposite, most charging devices were installed for the usage of public transportation. The policy inclination is one of the key reasons that led to the low private requisition of EVs in China. Besides, other factors such as the low brand diversity of EVs and consumer culture of advocating high fuel consumption in China also constrained the private EV sales. We will illustrate these points later.

China's policy is more inclined to develop the usage of BEVs rather than PHEVs. Two reasons lead to this policy preference. First, there is an urgent demand of clean transportation technologies to decrease the deteriorating local CO_2 emissions. As shown in diagram 7.4.1, the CO2 emission was growing dramatically during the last decade. In 2010, the CO_2 emission from the transportation section reached 508 million metric tons. As the increasing demand of vehicles and fast development pace of urbanization, the CO_2 emission from the transportation section would definitely increase even more dramatically in the future. Therefore, China planned to achieve a totally clean vehicle era without the transition of HEV dominance in EV market. Second, China's EV domestic hybrid technology is still behind the advanced level of foreign EV brands. Therefore, the domestic vehicle companies focus more on the technology development of BEVs than HEVs. The policy inclination led to the low sale record of PHEVs in China, not only from government procurement, but also from private EV purchase.

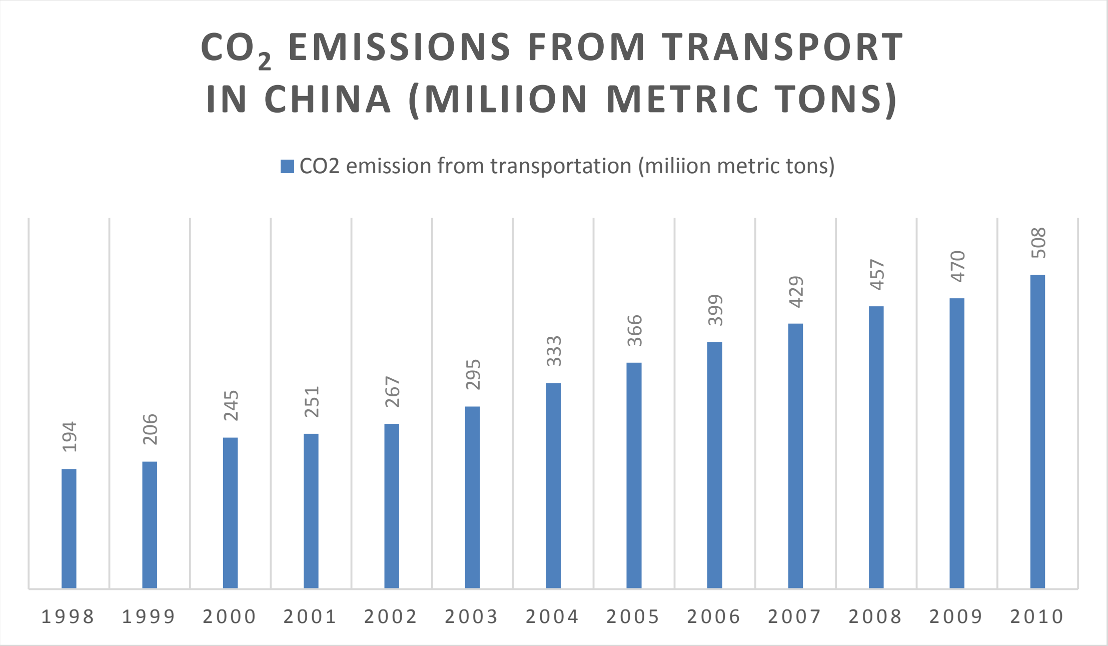


Diagram 7.4.1 CO_2 emissions from transport in China

Data source: ("CO_2 emissions from transport," 2013)

To protect domestic EV OEMs, China rejected to give consumer subsidies to foreign EVs. For instance, the Chevrolet Volt which entered China's EV market from the fourth season of 2011, did not receive any consumer subsidies from China's policy. Chevrolet Volt uses the lithium battery with 16kWh which allows 80 km driving range during the use of the battery. Besides, the 1.4 L energy generator can provide extra 490 km driving range. This type of PHEV entered the market of the US from 2010. The price in the US is 32,500 US dollars after tax subsidies of 7,500 US dollars. Since no subsidies have been approved for Volt, besides the import taxes, the price of the Volt in China is really high as 498,000 CNY which is around 81,382 US dollars. Besides, other imported EVs, such as LexusCT200h, Toyota Prius, have no subsidies, either. The luxury EV brand, Tesla Model S also announced to enter China's market by the end of 2013. And until now, no policy incentives have been planned to give to Tesla EVs.

Differently from China, the US did not constrain its policy incentives to domestic EV brands. Foreign EV brands, such as Toyota Prius and Nissan Leaf which all enjoyed the subsidies. Providing subsidies to foreign EVs will lead to a risky situation that high profits of EV sales will be swept away by foreign EV manufactures. In China, It will even threaten the development of domestic EV manufacturers, which is recent behind the technology level of foreign EV brands. However, the policy bias to protect domestic EV industry indeed limited the expansion of EVs dramatically during the last five years.

Second, the policy towards private purchase of EV only lasted for two years in the five demonstration cities. After the termination of the policy at the end of 2012, no following policies haven been issued. The private EV sale, therefore, almost become stagnant since then. The policy vacancy in private EV purchase on one side reflects the bad performance of the private EV sale, on the other hand, it also shows the government policy is more oriented to public EV development. The policy discontinuity cause all the efforts of stimulating private EV purchase before becoming naught. It would give automobile manufactures a misleading signal that the diffusion of passenger EVs is not key development targets of China's government, which means keep investing in passenger EVs would meet many more difficulties and hard to get profit. It would also frustrate EV's enthusiasts who have planned to purchase EVs, but changed their minds since the disappearance of subsidies.

Besides, many EV policies have a long time delay from the announcement of the policy to the effectiveness of the policy. For instance, the central government has issued the plan of reaching 1 million EVs by 2015 in "the national 12th five year plan" in 2007. However, the first substantive policy of "Ten cities, thousands vehicles" came out two years later in 2009. The policy of encouraging private EV purchase even came out one more year later in 2010. Many media reported that the new policy towards private purchase of EVs will come out soon in many major cities of China during the first half year of 2013, but until now, no official policies have been issued by the central government. What have been shown to the public now is a grand plan with not timely and effective actions. Undoubtedly, the time delay of policy effectiveness will delay and impact the process of EV development as well.

Third, local protectionism, which means local governments tend to be in favor of local EV brands for the government procurement, created a vicious competition environment for EVs. In the past policies, local government were responsible for paying the subsidies appropriated from the central government. Besides, many local governments also provide extra subsidies for EV purchase. For instance, Shanghai and Hangzhou governments provide extra 60,000 CNY subsidies to BEV purchase and 50,000 CNY to PHEV purchase. Hence, local governments hold strong decision-making power towards the types of EVs for government procurement. Behind every demonstration city from the "Ten cities, thousands vehicles" project, there is a certain EV manufacture. For instance, the BYD in Shenzhen, Beiqi Foton in Beijing and Shanghai Automotive Group in Shanghai, JAC in Hefei, etc. The extra subsidies to EV manufactures come from the fiscal revenue of local governments, and the local fiscal revenue largely come from the taxes income from the local companies; which leads to the local governments' purchase preferences of local EV brands to increase its own tax income.

7.4.2 RS of consumer cultures

Due to the high cost of EVs currently, the high consumption group should be an important target group who do not seem price as the critical criteria for cars. However, in China, not only the luxury EVs are limited for purchase, but also the EVs are not welcomed by the high consumption group. Compare to the clean EVs, high consumption group in

China is in favor of large gas guzzling sports cars or SUV in order to show their status. Low carbon life and green environment are not a major consideration in their consumption awareness. Not many people would take owning an EV as a social labeling to show their attitude towards the environment. Unlike in the US, where many celebrities showed off their EVs to build up a good public image, such as some famous entrepreneurs like Jeff Skoll and Larry Page, and Hollywood starts like Schwarzenegger and Brad Pitt, etc., In China, owning EVs is hard to be a popular culture.

On the opposite, the average consumption consumers prefer low fuel consumption vehicles. However, the high upfront cost of most EVs also make them unattainable to the average consumption consumers, which also led to the low sale of private EVs in China.

Consumer cultures were shaped by a cumulative previous consumption behavior and social factors. They are hard to be shaped by external policies or factors in a short term. Therefore, to overcome this drawback, the EV market should cater to the consumers' consumption habits and preferences and provide more diversity EVs to different target groups in order to enlarge the EV diffusion.

7.4.3 RS of product diversity and market position

In China, there are no clear market positioning for all the available EVs. The majority of EVs in China are middle or low consumption EVs. The luxury EVs launched to the market quite late and are very limited, such as BMW i series. There is still a big room for the growth of China's per capital vehicle holding quantity. In the future, China is also seemed as a big market for private car. Therefore, building up accurate market position for each type of EV can help it get through the difficulties of customer's acceptance. Only by understanding and meeting the needs of specific customer groups, and providing a variety of EVs to meet the demand of all different customer groups, can EVs have a bright future in China.

8 Conclusion and recommendations

8.1 Conclusion about the RS of EV system for urban mobility and strategies

In this research, to achieve our research objective, “investigating the reverse salient, which could be described as the critical technical hurdles and social barriers, of EV system for urban mobility”, we firstly studied all possible EV system configurations including the physical EV parameters and related infrastructure parameters. Based on the findings, we consulted four automotive industry experts and reviewed 34 literatures from scientific journals, business reports and government reports. The results from two ways are compared and validated to find out the ultimate conclusion of RS for the EV system for urban mobility. It also theoretically contributes to the application of RS theory by validating the reliability of combining morphological analysis with expert interviews. At last, an analysis of the RS of the development of EV system in China was conducted to give policy suggestions to China’s central government.

The designed research questions are answered as below:

1.1 What are the key parameters and values for the physical EV design?

The key parameters for physical EV are energy storage type, electric motor type and vehicle configurations. The values for energy storage type are batteries, fuel cell, super capacitor and flywheel. The values for electric motor type are AC induction motor, permanent magnet synchronous motor. The values for vehicle configurations are series, parallel, EM drive the wheel solely.

There are also many other components and sub-systems within the electric vehicle, but only critical components which can be combined to recognize different vehicles are considered here. After consulting experts, the “electric motor type” was deleted from the final EV system parameters, because as explained by experts, the electric motor technology is very advanced. In the whole EV system, electric motor is a forward parameter which is not RS for the EV development. Adding EM into the morphological field does not contribute to the finding of EV configurations.

1.2 What are the key parameters and values for the IEV deployments?

Only one parameter is considered for the IEV deployment: the type of infrastructure for electric vehicle. The values for the type of infrastructure of electric vehicle are level 1 charging station, level 2 charging station, fast charging station, battery swapping stations, hydrogen refueling stations and existing gas stations.

1.3 What are possible configurations of EV system?

Three parameters construct the final morphological field for exploring all possible EV system configurations, they are: energy storage type, vehicle configuration and infrastructure type. After the consistency assessment, incompatible configurations are filtered out. Finally we concluded 45 possible EV system configurations, as listed in Addendum II. All the configurations can also fit in general electric vehicle categories, such as battery electric vehicle, fuel cell vehicle or hybrid electric vehicle, etc..

By answering the three sub-questions, we got the answer for the first research question. Then based on the possible configurations, we consulted four automotive industry experts about the critical technical hurdles and social barriers for these types of electric vehicle systems, which answered the questions 2.2: "**What is the RS of EV system for urban mobility, based on morphological analysis and expert interviews?**" We also reviewed 34 literatures which have concluded some drawbacks of electric vehicle technology or social obstacles to answer the questions 2.1: "**What is the RS of EV system for urban mobility, based on literature review?**", We compared the two results and further answered question 2.3: "**What are the similarities and differences between the results from question 2.1 and 2.2?".**

The final conclusion about the RS of EV system for urban mobility is concluded as following, which can also be seen in addendum III.

RS for BEV

- Technical hurdles of the battery

  Both literatures and experts agreed that in general, the BEV technology is quite mature, and there is no significant technical hurdle for the diffusion of BEV. The remaining drawbacks of the BEV technology come from the vehicle battery and thermal management system. Elaborately, the technical RS of BEV are: the hidden safety problems induced by the battery; short life span of the battery; low energy capacity of the battery; and heavy and big size of the battery.

  - Improve thermal management system

    The strategy for improving it is also by improving thermal management system which can control the temperatures of batteries during charging, discharging and ambient changing situations. How to develop a compact, low-weight, and high effectiveness thermal management system is a technical research goal to improve the technical hurdles of the BEV.

  - Extend battery life span

    To extend battery life span and provide more durable batteries, we should continue to focus on technical breakthroughs that might be derived from innovations in battery chemistry.

  - Provide battery leasing opportunities

    If the batteries can be borrowed instead of owned, the replacement cost of BEVs can be omitted. But, who can take the high costs of owning all the batteries is an unknown question, should it be the battery production companies which can lower the costs by mass production, or should it be the automotive companies which are eager to push their BEVs into the market? Further research may be needed to analyse the feasibility of this business model.

- Customer acceptance of the price, occasional range anxiety and lack of infrastructures

  First, the high overall cost including the upfront cost, maintenance and replacement cost of the battery. How to provide an effective incentive mechanism to encourage BEV purchasing is a significant challenge for governments and BEV industries.

  Second, urban citizens not only need basic daily driving, but also require occasional long distance driving. The current BEV range is far enough to provide this requirements, therefore how to meet the occasional range anxiety is also a RS for BEV adoption.

  Third, the EV diffusion and charging infrastructures are chicken and egg problem. Without accessible infrastructures, no one would purchase EVs; on the other side, without large diffusion of EVs and suitable policies for the IEVs, no private sectors would like to invest in charging infrastructures. So who should invest in these charging devices installation and how to manage the payment system are questions for each city and country that plan to push EV diffusion.

  Besides, the installation of charging infrastructure for urban areas will be very costly, because different from individual dwellings which has their own electric outlets, there will be a huge capital cost to install all the charging devices for urban areas. Therefore, to improve the EVS for urban area, providing charging options in dwelling areas and business areas are critical.

  - Technical improvement, mass production and effective incentives

    There are three ways to decrease the battery price to an acceptable level. First, a further advance in battery technology is required. This may require developing new battery chemistries or continuing the technology improvement of lithium-ion. Second, Mass-production of batteries will also help to reduce the cost by economies of scale. At last, purchasing incentives towards BEVs will also help to lower the upfront cost of BEVs to an acceptable level. An effective incentive mechanism to encourage BEV purchasing is a significant challenge for governments and BEV industries.

  - Provide charging infrastructure

    The current battery capacity is sufficient for the daily driving demand in urban areas after a full charge of the vehicle battery during the night. However due to customers' distrust about the driving range of BEVs, providing more charging infrastructures is critical to solve the range problem. On the opposite, developing more advanced battery technology in order to provide longer driving range for the vehicle is not necessary, because this will induce an even higher vehicle cost which is mainly blocking the BEV diffusion.

  - Car leasing or car sharing

    Changing the car ownership model from personal owning to car leasing or car sharing can help to reduce the RS of high upfront cost of the BEVs and occasional range anxiety. If people can promise to use BEVs for daily use, automotive company can let a regular vehicle for the need in holidays. If this kind of scheme can be offered to customers, maybe the volume of BEV usage will increase significant straightway. The provision of vehicle leasing can make up the short range disadvantage of BEVs today and fit customers' driving lifestyle.

    Car sharing is a similar business strategy model which also helps to decrease the obstacle of BEV, and improve its diffusion. In this case, people do not own any vehicle, but they can share any available vehicles by becoming a member of the car sharing community.

  - Scheme on public private partnership projects for charging infrastructures

    The chicken and egg problem needs public-private partnership projects to solve. In the initial phase, government have to invest most, and encourage private sectors to invest and provide technologies to install the IEVs. For instance, the current American IEV projects, the EV project and ChargePoint America, which installed charging stations throughout the east and west coasts of the US, are partially funded by two manufactures: ECOtality and Coulomb Technologies through PPP projects. The charging infrastructures can also contribute to customer acceptance of EVs.

- Global environmental concerns

  Although BEV avoids the CO_2 emission from vehicle exhaust vent, the electricity being charged to the batteries might be produced by a not so efficient way, such as coal-fired plants, which may produce even higher level of GHG emissions to the global environments. Therefore, the large adoption of BEVs may just transfer the pollution problems from local and urban areas to the energy production plants. For the countries which are still largely using coal-fired plants, the W2W emission of BEVs will be significant RS which will constraint BEVs' expansion due to environmental concerns.

  - Improving the electricity production ways by using cleaner primary energy sources

    To solve the W2W GHG emission concerns, the most efficient way is to inherently change the primary energy source of producing electricity to cleaner ones. The available primary sources are fossil fuel which includes coal, gas and oil; nuclear; biomass; and renewable energy sources, such as solar thermal, wind, tide and hydro, etc. Nowadays, the energy being used the most globally is coal which takes the amount of 41% of all the energy being used for electricity generation, but produces the highest GHG emissions. Among all the primary energy sources, renewable energy, biomass, and nuclear provides relatively the lowest life cycle GHG emission, compare to fossil fuel options. Therefore, changing current electricity generation way to cleaner primary sources not only will help to make the overall CO_2 emission of BEVs cleaner, but also contribute to the global environment significantly.

  - Provide authentic and reliable data of energy efficiency level

    To convince customers that the use of BEVs will make a significant contribution to the local and global environment, more reliable data of the current way of electricity production and overall energy efficiency level of BEVs should be provided to the public. Make the information transparent and accessible to the public can attract potential buyers for BEVs.

- Potential negative impacts on power grid

  The large diffusion of BEVs will depend on the power grid to provide a large amount of electricity. Since most charging events will occur during the same period at night, which will give a huge load to the power grid. For instance, a level 2 charging would be around 6.5 kWh of power, roughly equal to the peak power consumption of home power consumption. However, since EVs are moving around and may charge in different places during the day, if a few EVs charge together at one spot, the electricity capacity would be overloaded. Equivalently, if many EVs are charged at within the same short period, the additional load on the grid would be dramatic. Thus the potential negative impacts on the power grid need to be taken into account when large diffusion of BEVs is going to take off.

  - Smart charger

    To solve the overload power grid problem, a smart charger, which use an on-board timer to control the charging starting time can guarantee the battery being charged during off-peak period, such as what has been used in the Nissan LEAF. Other devices such as real-time energy price monitor can help EV owners to charge when the price is low.

  - Collaboration with utility companies

    Besides the provision of smart grid, there are many regulatory concerns towards the electricity provision and usage, payment and standards of the charging facilities should be discussed and agreed among charging infrastructure providers, business owners and power utilities. Therefore, the collaboration and coordination among these actors are crucial to guarantee the reliability and efficiency of charging infrastructures.

RS of conventional HEVs and strategies to overcome

The conventional HEVs share the same technical hurdles of short life span and potential safety problems as BEVs. It also shares the customer acceptance barriers of the high cost and safety issues. The strategies mentioned above for the associated hurdles for BEVs are applicable for HEVs as well. So, we will not repeat the same contents again.

- Negative impacts on local environments

  The specific hurdle for conventional HEVs is the concerns of adverse impacts on local environments. Although the use of the battery to retrieve the energy lost from braking in conventional HEVs improves the energy efficiency of the vehicle, the usage of combusting gasoline or diesel is still producing a lot of GHG emissions to the local environments. Hence, the hurdle for encouraging the usage of conventional HEVs large results from their low contribution to the local environments.

  - ➢ The transition from conventional HEVs to PHEVs or EREVs

    The conventional HEV does not provide opportunities to charge on the power grid, which is inferior to PHEVs and EREVs in terms of environmental benefits. Therefore, there is a need of transition from HEVs to PHEVs or EREVs in the future to better use the advantage of the batteries.

RS of PHEVs and EREVs

We combine the results of PHEVS and EREVs because they share the same RS. Same as BEVs, PHEVs and EREVs also share the same technical hurdles of battery and customers' acceptance concerns towards the high overall cost of the vehicle and safety issues. It also shares the same concerns about adverse impacts to the local environment with conventional HEVs. However, the PHEVs/EREVs allow the usage of charging the battery on the grid, it is thus cleaner than conventional HEVs in terms of producing local pollutions. The specific RS of PHEVs/EREVs are:

- The lack of incentives of charging vehicle batteries

  The real charging frequencies of PHEVs and EREVs by users are in doubt. Do users prefer charging the vehicle batteries to just refuelling to the gas tank? Due to the lack of charging infrastructures in public, employers and commercial parking lots, we doubt that customers would tend to just refuelling the gas tank by using existing gas stations rather than looking for a charging spot. Although many incentives have been given to the HEV purchasing, there still lacks incentives to encourage HEV users to charge the vehicle batteries. For example, if an employee is using a company owned HEV, and no charging facilities are provided in the company. He or she would prefer refuelling the vehicle by spending the company's money rather than charging it at home during the night by spending his own electricity fee.

  - ➢ Provide incentives and charging facilities for encouraging PHEV/EREV users to charge the battery

    The incentives of tax free and lower the cost of the vehicle only solve the problem partially, how to make users fully apply the battery into use is the critical challenge after the purchase. Companies which encourage the purchase of PHEVs/EREVs should also provide equivalent charging benefits as providing subsidies for gas expenses. Again, providing charging facilities is crucial to the fully usage of the benefits of charging the batteries.

RS of on-board and off-board FCEVs

Both the on-board and off-board FCEVs share the same well to wheel global GHG emission concerns as BEVs. They also have high overall cost and low customer acceptance about the safety issues.

- Technical RS of high cost, low life span and safety problems for FCEVs

  The technical RS of FCEVs are high cost, low life span, and safety problems of the fuel cell stack.

  - ➢ Technical improvement of the fuel cell

    The possible technological improvement could be considering new materials development for the membranes, advanced design, manufacturing, thermal management, etc. To provide a cost-effective safety protection system including the cryogenic storage for hydrogen and safety refueling devices, which can meet the customers' safety acceptance level is critical to its success.

- Lack of hydrogen infrastructures for off-board FCEVs

  Unlike on-board FCEVs, which can use the current gas stations to refuel gasoline and produce hydrogen on-board of the vehicle, off-board FCEVs really need hydrogen infrastructures to provide opportunities to power the vehicle. Without hydrogen infrastructure, the diffusion of off-board FCEVs cannot happen. The situation is even worse than BEVs, since at least BEVs can be charged at home.

- High cost, heavy weight, big size and environmental concerns of on-board FCEVs

  The technology of on-board FCEVs is available, but this vehicle includes not only the big fuel cell tank, but also a gas tank and extra reformer for producing hydrogen. The high cost, heavy weight induced by the complex system will be significant hurdles for on-board FCEVs. Besides, the on-board production way will produce lots of CO_2 emissions as well. This will be a hurdle of not using this type of FCEVs since the inferior environmental contribution.

RS of flywheel EVs and HEVs

- Technical reliability and low energy capacity

  The greatest RS of flywheel vehicles come from the technical reliability. The usage of flywheel will disturb the operation of the vehicle and generate uncomfortable driving experiences for customers. Besides, the heavy weight and low capacity are also blocking the flywheel from being a feasible energy storage solution for EVs.

RS of super capacitor EVs and HEVs

- Low energy capacity and high cost

  The main hurdle for super capacitor being used as energy storage system for EVs is still the high cost and low energy capacity. However, it is seemed as a feasible solution for combining with batteries to provide better driving performances.

RS of charging infrastructures

- High capital investment for urban areas

  One critical RS for the EV's diffusion is lacking of charging infrastructures. For urban areas, since the charging infrastructure are needed in more multiple apartment complexes such as parking lots, street sides, and in employer areas. Different from individual dwellings which have their own electric outlets, there will be a huge capital cost to install all the charging devices for urban areas. Therefore, to improve the EVs for urban area, providing charging options in dwelling areas and business areas are critical.

- Potential negative impacts on the power grid

  Second RS towards the allocation of IEVs are the influence of charging actions to the power grid. A level 2 charging would be around 6.5 kWh of power, roughly equal to the peak power consumption of a home power consumption. However, since EVs are moving around and may charge in different places during the day, if a few EVs charge together at one spot, the electricity capacity would be overloaded. Equivalently, if many EVs are charged at within the same short period, the additional load on the grid would be dramatic.

  - Hence, to large diffuse EVs, we need to make sure that our power grid can provide this amount of power and regulation policies should be made to better manage and balance the load in order to provide stable, safety and robust power supply for EV owners

  - The need to install charging infrastructures in dwelling areas and business areas

    To improve the EVS for urban area, providing charging options in dwelling areas and business areas are critical. The optimal allocation of IEVs for urban areas are level 2 charging stations in apartment complex parking places and business areas and a few fast charging devices in charging stations for opportunity charging need. The level 2 charging can provide faster charging time for a relatively bigger battery than level 1 charging station.

  - Scheme on public private partnership projects for charging infrastructures

    As mentioned earlier, PPP projects are good ways to break the chicken egg problem. It is an efficient way to speed up the development of the whole EV system.

- Damage to the battery life of DC fast charging

The current technology of DC fast charging will still decrease the battery life. The faster charging a large amount of energy into the battery, the stronger damage to the battery life. Compared to short term charging, the disadvantage of fast charging may not be applicable to daily charging usage of EVs. It is more suitable for opportunity charging in urban areas.

RS of battery swapping infrastructures

The main RS of battery swapping infrastructures is high capital investment, logistic difficulties and lack of large diffusion of BEVs.

- Logistic difficulties of battery swapping infrastructures

  The logistics RS is about the allocation of batteries in different locations and matching the type of batteries with different types of vehicles.

RS of hydrogen refuelling infrastructures

There is no technical hurdle for hydrogen refuelling infrastructures. The only RS comes from the social concerns that the cost capital investment of the infrastructures.

- ➢ Within the boundary of urban areas, maybe off-site producing is a more cost-effective option, but of course will induce safety issues towards transportation and storage in urban areas. These drawbacks require time and demonstrations to convince customers that hydrogen stations are safe to be used.
- ➢ As the adoption of PPP project, the construction of hydrogen infrastructures can also borrow this strategy.

To apply our findings of RS for urban mobility, we further analysed the EV market and EV policies in China in order to answer the research question 3: ***“What is the main RS of electric vehicle system in China and how to improve it?”***

The main RS of China’s EV market does not mainly come from technological aspect, but results from the social barriers which includes high cost of the battery, unfavorable political police environment, disadvantageous consumer cultures and poor EV market position and diversity.

The central governments’ acts and local government’s policies largely control and impact the development of EV in China, which is the most severe RS. The political RS of China includes: first, the strong policy biases of policy inclination to public EVs rather than private EVs; to the purchase of BEVs rather than PHEVs; to limited cities rather than nationwide; to subsidy domestic EV brands rather than all qualified EV brands including foreign ones. Second, policy delay and discontinuity also restricted the EV diffusion, especially for private purchase of EVs. At last, China’s local governments tend to be in favor of local EV brands for the government procurement. The strong local protectionism created a vicious competition environment for the development of EV in China.

To create a better policy environment for the development of EV. Three suggestions are given to China’s central government:

- First, China’s central government should adjust the current policy to make a balance between the encouragement to public EV transportation services and private EV usage. The subsidies to private EV purchase should be reissued and enlarge the benefit cities to nationwide. By doing this, on one side, potential EV customers can take advantage of the subsidies and increase the EV demand; on the other side, domestic EV producers will be encouraged to invest more on EV product development and market positioning in order to enlarge its market share by providing good quality and differentiated products and services to customers.
- Second, China should also increase its financial supports to the development of EV technologies by providing individual financial subsidies to qualified EV research projects. Only with the continuous technology progress can domestic EV brands enhance and remain their competitive worldwide in a long term. Besides, the plan of jumping to BEV driven market without the transition from ICVs to HEVs did not work well in the short term. China should keep encouraging the research, production and purchasing of PHEV in both public transportation services and private usage.
- Third, the central government should take back the rights of granting subsidies to EV projects from local governments. This action can effectively control the local protectionism and create an environment of fair competition. The government procurement plans from local governments need to be approved by the central government before granting the subsidies.
- Four, China’s government can consider giving private purchase of foreign EV brands a fairish amount of subsidies, which not only create a survival space for foreign EVs, but also increase the sense of competition to domestic EV brands. The subsidies should be lower than the ones to domestic brands, but make a balance between the price of domestic products and foreign ones.

Secondly, the consumer culture in China also constraints the diffusion of EVs. The culture of being proud of owning an environmental friendly car has not been formed in China. The high consumption group in China are more in favor of large gas guzzling sports cars or SUVs in order to show their status rather than owning a luxury EV. To the average consumption consumers, the high upfront cost of most EVs also make them unattainable.

Thirdly, no clear market positioning for all available domestic EVs is also a key reason for the failure of the EV market in China. The current EVs in China are concentrated at middle and low consumption types. These EVs are not welcomed by high consumption consumers in terms of driving performance and exterior. They are not popular among average consumption consumers since the high price of the vehicle.

- To overcome these two drawbacks, trying to shape customers’ consumption behaviour cannot meet the urgent needs. Consumer cultures were formed by a cumulative previous consumption behaviour and social factors. They are hard to be shaped by external policies or factors in a short term. Therefore, to overcome this drawback, the EV market should cater to the consumers' consumption habits and preferences and provide more diverse EVs to different target groups in order to enlarge the EV diffusion. For instance, to the high consumption group, EV producers should focus more on the driving experience and requirements of high driving speed, high acceleration speed, luxurious interior and exterior designs. Artificial noises can also be installed in these types of EVs in order to meet the psychological showing off needs of drivers. To the low and middle consumption consumers, policy subsidies are crucial to decrease the upfront cost of EVs. In the future, only by understanding and meeting the needs of particular customer groups, and providing a variety of EVs to meet the demand of all different customer groups, can EVs enlarge their market.

Besides all the suggestions to the short term EV development in China, there are two suggestions to the China's central government about the development of EV in the long term.

- ➢ First, government subsidies should be decreased gradually after the EV sales reach a certain level.
- ➢ Second, China relies on coal energy sources heavily, China is also the biggest coal production country. It is hard to get rid of the current electricity production way in a short term, but China should pay more efforts on substitutions such as green energy sources or nuclear power and research on ways of to improve the energy efficiency during the production process in a long term. Only by providing cleaner energy production way, the EVs in China can become a truly sustainable vehicle.
- ➢ Third, although in the current phase, government regulation is the most critical RS for the development of EV system, the development of charging infrastructures and battery technologies are also important aspects that China's government should not neglect.

8.2 Theoretical conclusion and future research recommendations

This research exams the reliability of using the combination of morphological analysis and expert interviews for exploring reverse salient of the electric vehicle system. Previous researches about exploring RS for large scale technological system have not used this method framework. They either reviewed the history of technological development based on literature reviews or used quantitative data to analyze RS. The character of complexity and strongly dependence on social influencing factors from EV system make it hardly a quantifiable research object. Besides, no literatures have analyzed the whole electric vehicle system considering not only the physical EV designs, but also their associated infrastructures. Therefore, we use morphological analysis, a typology exploration method, to investigate all possible EV configurations thoroughly. Based on the configurations, we consulted four automotive industry experts to find out the technical hurdles and social barriers for each type of vehicle.

To validate the research results from our designed research framework, the research pathway 2, we also collected the RS from reviewing 34 literatures, which is named the research pathway 1. The confrontation of two research results, as shown in Addendum III, demonstrates some similarities and differences. The results from research pathway 2 covered all the results collected from research pathway 1. There are no missing critical points from research pathway 2, based on our research. Besides, it also provides external discussable topics to our research.

8.2.1 Strengthens and restrictions of the methodology

Theoretically, this method framework contributes to the application of the reverse salient theory in terms of providing a research method for exploring RS and enlarging the application domain into electric vehicles and their corresponding infrastructures. Previous researches about exploring RS for large scale technological system did not use this method framework. They either used quantitative data to analyze RS or reviewed the history of technological development based on literature reviews. In our research, we discussed RS by consulting EV specialists based on the discussion of the structured EV types derived from morphological analysis.

The confrontation results as shown in section 6.3.1 demonstrate that the methodology of combining morphological analysis with expert interview to explore RS is doable and reliable and even advanced than traditional literature reviews. However, there are some restrictions about this methodology as well.

The advantages of the pathway 2 are in two aspects. Firstly, it is analyzed based on a list of exhaustive physical EV design solutions by employing morphology analysis to structure technological solutions into different categories. Secondly, it includes adept industry pro’s opinions and perceptions about the EV development, so the results are more application and realistic oriented, which just make up the disadvantage of pathway 2, which is more theoretical oriented. Besides, expert opinions gave us fresher and on time information rather than out dated conclusions. In summary, the information being collected from expert interviews are practical, timely and effective. The disadvantage of pathway 1 might be it is hard to check very detailed technological problems such as focusing on one small component of the vehicle when we discuss the RS of EVS, or quantifiable data of the costs, the emission level, energy efficiency level or driving range, because the experts being interviewed pay attention to and expertise in a higher level of analysis. This drawback can be improved by combining the result with pathway 1.

On the other hand, the research path 1 collected RS from literature reviews, the scientific literatures really focus on detailed technological drawbacks. It provides a theoretically view of the past research results of the situation in each type of EV designs. The results are reviewed by multiple professionals before they were published, therefore, they have highly representatives and reliability. But the drawbacks of the pathway 1 may be that published papers are relatively old fashioned and rigid in a constraint research boundary or topic. It is hard to see the whole picture of the development of the entire electric vehicle system. Besides, literatures are theoretical oriented; they may lack current industry information and therefore lack of values to make strategy plans for the automotive industries and governments.

As a result, we propose to combine the two research pathway in the future research of exploring RS of any other large scale technological system. The advantage of doing this are: Initially, the two research pathways can complement and correct each other in order to reach a more comprehensive and accurate results. Therefore, the concluded results based on the confrontation of the two pathways are meaningful in terms of providing both theoretical and business-oriented; past information and on time intelligence; and exhaustive analysis of all possible EVS designs for exploring technical hurdles and social barriers in a neutral view.

The restrictions of combining the two research pathways might be firstly, it lacks of validation based on application in other type of technological systems since this is a new method framework for exploring RS; Secondly, it is quite time consuming of executing three methods, just like our research, because of time constraint of five months, the work of studying and executing the multiple methods including literature review, morphological analysis and experts interview is relatively heavy; therefore we may have neglected some blocking points of the EVS during the limited number of interviews and unexhausted literature reviews.

8.2.2 Recommendations for future researches

The future research can focus on the following topics:

Fist, further research can apply this methodology to investigate the technical hurdles and social barriers for other large scale technological systems. This will enlarge the application of RS theory and also validate our research framework in other technological domains.

Second, due to time limits, this research only focuses on the boundary of urban mobility. To enlarge the research boundary, further research can investigate possible EV system designs for suburban, rural areas, or freeways mobility.

Third, many researches about the EV technology and policy analysis about EVs, but the research topics related to psychological analysis of EV customers have not been worked on much. This kind of research may require customer psychology, economic, social, marketing and technical analysis.

Since the RS of EVs is from social reasons, and the customer acceptance critically decides the fate of EV diffusions, there is a demand of exploring customer interests and demands towards EVs. We have listed the RS from customer acceptance as high cost, occasionally range anxiety and safety concerns, but how customers value these factors is still unknown. This is also a restriction of our research that we did not directly consult

EV users or potential users to get a more detailed customer demand results.

Further research can focus on exploring customer physiological measurements towards these factors. The current EV types in the market, such as Chevrolet Volt, Nissan LEAF, etc., could be used to gauge customer interests. The expected research result could be a map of different weighted demand and interest factors by consulting EV customers. It could give the automotive industry and governments a signal to accentuate the development policy and business strategies towards realizing the explored demands.

Besides, by researching on customer interests and demand, not only the average customer demand should be explored, but also the classification of different types of customers and their interest are highly required. There might be some consistent interests among a certain age range customers, gender, occupation, interests, marital status, and so forth. For instance, a man with a family of his wife and three children may have greater occasional range anxiety and bigger type of vehicle compare to a singled man, because the man with a family needs an SUV with five seats and require EVs of travelling for holidays, but the single man may only need a two seats vehicle and a 100 kilometres' range EV is sufficient for his daily demand. For holidays, he may prefer other transportation ways, such as bus or train. There is another discuss towards the transportation preferences of the new generation, the generations born after 1990 or later. For this generation, as the advent of widespread public transportation network, the more and more server congestions due to urbanization, the boom of new car leasing businesses and stronger environmental concerns and stricter policy penalties towards CO_2 emission and smog precursor emissions from vehicles, they may need less and less personal automotive as the old generations. Such an exploration of different demands of different classified customers is valuable for the automotive industry to launch diverse types of EVs to the targeted customers. Some technological performance could be changed according to the results as well in order to satisfy customer demands.

Therefore, for future research of EV deployment, we recommend exploring more influencing factors and their weights in customers' need, explore the average customer need and classify different types of customers for different EV types. Based on these results, researchers can design compatible EV configurations by modifying technological component in order to achieve the technological performance required by the counterpart customers. The results will help current EV types to improve and stimulate new type of EVs. The automotive industry can use this information to plan better strategies into the targeted market, and government authorities can make better policy to assistant the EV development in order to achieve a greener environment.

Fourth, further research can focus on the policy structure planning for the infrastructures for electric vehicles for different countries according to their specific political structure, culture and country conditions. The questions for solving are such as "how to better arrange PPP projects for IEVs in order to improve and better deploy the electrification transportation."

Reflection

About the EV system

Through the process of completing this thesis, I have learned a lot about the history and the status quo of electric vehicle system. The electric vehicle does not solely exist in the market; the failure and success of EV technology is influenced by multiple factors involving in the whole EV system. I have sorted out the relationship between EV technology and other factors. And I also recognize the importance of infrastructures, electricity production and political policies to the survival of EVs.

Without a large spread of EV infrastructures, EV is like a heart without blood which provides power for it. To enlarge the diffusion of EV, providing related infrastructures are critical to its success.

Without government regulation, EV is hard to compete with ICVs in a free market. Government regulation plays a key role in the initial stage of the development of EV. According to the specific national features, Governments are responsible to provide purchase subsidies, organize PPP projects for the installation of infrastructures, financing the research and development of EV technologies. During the process of government regulation, other problems may come up, such as local protectionism, policy biases and termination. Government should fix these problem timely in order to speed up the development pace of EV.

Without a greener electricity production method, the large diffusion of EV may not be an optimal solution in the long term. It will only transfer local pollutions to remote electricity production plants. The overall GHG emissions may be even worse than before or not worth the cost of large amount of investment into EVs and new infrastructures.

For urban mobility, the most critical RS of EV system lies in multiple social barriers. The social barriers are different according to different perspectives from EV users, government authorities and EV producers, due to their different objectives towards EV. The social barriers are also different in different countries due to the different domestic technology level, consumer cultures and political structures. Therefore, the research results from morphological analysis and expert interviews are general analysis of the overall situation of EV systems worldwide. It is hard to say which RS is more severe than the others.

About the theory of reverse salient and morphological analysis

The origin of reverse salient has been studied in this paper. By understanding the cases from Hughes's book, the definition of RS has been identified, and categories into three perspectives: technological RS, economic RS and political RS. Technological RS usually occur during the nascent stage of the development of the technology. Economic RS happens when the technology just enters the market and without a particular scale of diffusion. Political RS usually occur when technology is transferred from one country to another. The study of the RS of EV system for urban areas also proofs this point. The high cost of EVs becomes one of the significant RS for EV system nationwide during the beginning of the market launch. From the case of China's EV development, it also proof that public policies are critical RS which decide the life and death of EVs.

It is a new point of combining morphological analysis and expert interviews to study RS in this paper. The pity is that no new EV configurations have been found by the morphological analysis. From the process of analyzing all the EV configurations, I feel that morphological analysis require strong technological background and experts' opinions to support the results. During this study, the interviewed experts indicated that all combinations are possible, but the practicality of each configuration requires many other analysis like the analysis of performance and cost effectiveness. Future researchers may focus on the new configuration development by organizing technology professional's seminars.

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Addendum

Addendum I Interview questions

Time: 1-2 hours/person; Interviewees: FCEV and BEV experts

Some notions such as MA and RS may be confused and hard to understand by industry experts, therefore we translate RS as drawbacks of components or sub-systems in our interview.

About possible configurations, drawbacks of EV designs:

1 What are key components of EV designs? How many types of EV designs would there be recently and in the future? What are they?

2 From the technological aspect, which components or sub-systems that are hindering the development of EV? why?

3 How to improve these drawbacks? Can we achieve it by current technology or what is the possibility of achieving it in the future?

4 Besides the technological drawbacks, are there any social factors, such as geographic dependence, culture dependence or policy influences, which are restricting the diffusion of EVs?

5 How to solve the problem induced by social negative impacts?

About possible configurations, drawbacks of the infrastructures of electric vehicle

6 How many different types of infrastructures are there for EVs recently and in the future?

7 From the technological aspect, which components or sub-systems that are hindering the development of the infrastructures of EVs? why?

8 How to improve the development of EV infrastructures? What is the possibility of achieving it in the future?

9 Besides the technological drawbacks, are there any social factors, such as geographic dependence, culture dependence or policy influences, which are restricting the development of the EV infrastructures?

10 How to solve the problem induced by these social negative impacts?

About possible configurations, drawbacks of the entire EV system, combining both physical EV designs and IEV deployment：

11 Considering both the physical EV and their related infrastructures, how many types of EV system would there be?

12 From the technological aspect, which components or sub-systems that are hindering the development of the whole EV system?

13 How to improve the whole EV system? What is the possibility of achieving it in the future?

14 Besides the technological drawbacks, are there any social factors, such as geographic dependence, culture dependence or policy influences, which are restricting the development of the whole EV system?

15 How to solve the problem induced by these social negative impacts?

About possible configurations of EV system for urban areas

17 For urban areas, which deployment of infrastructure and EV will be possible? why? Which one will be the best? why?

Extra questions for the FCEV experts

1 We know there are battery electric vehicle, hybrid EV, plug-in HEV and extended range HEVs. How many types of fuel cell vehicles can you categorize? What are they?

2 From the energy storage side, how many types of ESS can be used for FCEVs?

3 There are also some types of hybrid fuel cell vehicles. They combine fuel cell with battery, super capacitor or flywheel. What do you think of these hybrid types?

4 How about the electric motor, does FCEV need different electric motor from battery electric vehicles?

5 In my research, I am using three parameters to distinguish different electric vehicle designs. They are infrastructure, energy storage system and vehicle configurations. As shown in the form, I found out all the EV types. Do you have anything to add in this form? How about the vehicle configuration of FCEVs? how are they structured?

6 What are the challenges for FCEVs from pure technological perspective and social perspective? Why? How to improve them?

7 How many types of hydrogen refuelling infrastructures are there for FCEVs? What are they?

8 How about the location of hydrogen refuelling station? Where do you expect them being installed? At home, at work, commercial complex or on the highway?

9 What are the hurdles of the development of hydrogen refuelling stations? Why? Are they technological problem or social barriers? How to overcome these problems?

10 Many have discussed the safety issue of FCEVs. What do you think of this problem? Is it a technological drawback or just because of customers’ perception that FCEV is more dangerous?

11 If we compare BEV, HEV and FCEV, what are the advantages and disadvantages of FCEVs? What are the pros and cons of BEV and HEVs?

12 What are the challenges for BEVs, HEVs, super capacitor EVs and flywheel EVs? Are there any strategies to overcome these problems?

12 So for urban mobility, between BEV, HEV and FCEVs, where do you put your bets? Which one will be the optimal vehicle for urban mobility? Why?

13 From the well to wheel efficiency, is FCEV more efficient than BEV?

14 So among safety issues, cost, customer acceptance, government policy towards hydrogen infrastructures, technological obstacles. Which is the most severe problem?

15 Some mentioned battery ownership model in a different way, such as battery leasing or vehicle leasing models. Are there any business models suitable for FCEVs' diffusion in urban area?

Addendum II All possible EVS configurations

No. of configurations	**Energy storage type**	**Vehicle configuration**	**Infrastructure**	General type of vehicle
1	battery	EM drive the wheel	level 1 charging	BEV
2	battery	EM drive the wheel	level 2 charging	
3	battery	EM drive the wheel	DC fastcharging	
4	battery	EM drive the wheel	Batteryswapping	
5	Fuelcell	EM drive the wheel	Hydrogeenrefuelling	off-board hydrogen FCEV
6	fuelcell	EM drive the wheel	Gas station	Off-board hydrogen FCEV
7	flywheel	EM drive the wheel	level 1 charging	FEV
8	flywheel	EM drive the wheel	level 2 charging	
9	flywheel	EM drive the wheel	DC fastcharging	
10	flywheel	EM drive the wheel	batteryswapping	
11	supercapacitor	EM drive the wheel	level 1 charging	SCV
12	supercapacitor	EM drive the wheel	level 2 charging	
13	supercapacitor	EM drive the wheel	DC fastcharging	
14	supercapacitor	EM drive the wheel	batteryswapping	
15	battery+fuelcell	EM drive the wheel	level 1 charging	battery and fuel cell HEV
16	battery+fuelcell	EM drive the wheel	level 2 charging	

17	battery+fuelcell	EM drive the wheel	DC fastcharging	
18	battery+fuelcell	EM drive the wheel	batteryswapping	
19	battery+fuelcell	EM drive the wheel	hydrogenrefuling	
20	battery+gas tank	Parallel hybrid	level 1 charging+ gas station	plug-in HEV
21	battery+gas tank	Parallel hybrid	level 2 charging+ gas station	
22	battery+gas tank	Parallel hybrid	DC fast charging+ gas station	
23	battery+gas tank	Parallel hybrid	batteryswapping	
24	battery+gas tank	Parallel hybrid	Gasoline or diesel station	conventional HEV
25	battery+gas tank	Series hybrid	level 1 charging+ gas station	EREV
26	battery+gas tank	Series hybrid	level 2 charging+gas station	
27	battery+gas tank	Series hybrid	DC fast charging+gas station	
28	battery+gas tank	Series hybrid	batteryswapping+gas station	
29	battery+gas tank	Series/parallel hybrid	level 1 charging+gas station	PHEV
30	battery+gas tank	Series/parallel hybrid	level 2 charging+gas station	
31	battery+gas tank	Series/parallel hybrid	DC fast charging+gas station	

32	battery+gas tank	Series/parallel hybrid	Batteryswapping+gas station	
34	battery+flywheel	EM drive the wheel	level 1 charging	Batteryandflywheel HEV
35	battery+flywheel	EM drive the wheel	level 2 charging	
36	battery+flywheel	EM drive the wheel	DC fastcharging	
37	battery+flywheel	EM drive the wheel	Batteryswapping	
38	flywheel+supercapacitor	EM drive the wheel	level 1 charging	Flywheel and super capacitor HEV
39	flywheel+supercapacitor	EM drive the wheel	level 2 charging	
40	flywheel+supercapacitor	EM drive the wheel	DC fastcharging	
41	flywheel+supercapacitor	EM drive the wheel	batteryswapping	
42	Supercapacitor+battery	EM drive the wheel	level 1 charging	Super capacitor and battery HEV
43	Supercapacitor+battery	EM drive the wheel	level 2 charging	
44	Supercapacitor+battery	EM drive the wheel	DC fastcharging	
45	Supercapacitor+battery	EM drive the wheel	batteryswapping	

Addendum III RS of EV for urban mobility from two pathways

BEV		Pathway 1	Pathway 2
Technical perspective	Battery capacity	√ ×	×
	Safety problems	√	√
	Life span	√	√
	Size and weight	√	√
Economic-effective	Cost	√	√
Customer acceptance	Overall Cost	√ ×	√
	Occasional range anxiety	–	√
	Lack of charging stations	√	√
Other social concerns	W2W GHG emissions	√ ×	√
	Impact on power grids	√	√
Conventional HEV		Pathway1	Pathway 2
Technical perspective	Safety problems	√	√
	Life span	√	√
	Size and weight	√	√
Economic-effective	Cost	√	√
Customer acceptance	Overall Cost	√ ×	√
Other social concerns	W2W GHG emissions	√ ×	√
PHEV		Pathway1	Pathway 2

Technical perspective	Safety problems	√	√
	Life span	√	√
	Size and weight	√	√
Economic-effective	Cost	√	√
Customer acceptance	Overall Cost	√ ×	√
Other social concerns	W2W GHG emissions	√ ×	√
	Impact on power grids	√	√
	Lack of incentives of charging the batteries	–	√
EREV		Pathway1	Pathway 2
Technical perspective	Safety problems	√	√
	Life span	√	√
	Size and weight	√	√
Economic-effective	Cost	√	√
Customer acceptance	Overall Cost	√ ×	√
Other social concerns	W2W GHG emissions	√ ×	√
	Lack of incentives of charging the batteries	–	√
	Impact on power grids	√	√
On-board hydrogen FCEV		Pathway 1	Pathway 2
Technical perspective	Safety problems	√	√

	Life span	√	√
	Size and weight	√	√
Economic-effective	Cost	√	√
Customer acceptance	Overall Cost	√	√
	Safety concerns	√	√
Other social concerns	W2W GHG emissions	×	√
Off-board hydrogen FCEV		Pathway 1	Pathway 2
Technical perspective	Safety problems	√	√
	Life span	√	√
	Size and weight	√	√
Economic-effective	Cost	√	√
Customer acceptance	Overall Cost	√	√
	Safety concerns	√	√
	Lack of hydrogen Refuelling infrastructures	√	√
Other social concerns	W2W GHG emissions	×	√
Super capacitor EV and HEV		Pathway 1	Pathway 2
Technical perspective	Battery capacity	√	√
Cost-effective	High cost	√	√
Customer acceptance	Range anxiety	√	√

	High cost	√	√
Flywheel EV and HEV		Pathway 1	Pathway 2
Technical perspective	Battery capacity	√	√
	Reliability	√	√
	Size and weight	–	√
Customer acceptance	Safety concerns	√	√
	High cost	√	√

Addendum IV List of Technology Innovation Projects Approved for Financial Incentives

List of Technology Innovation Projects Approved for Financial Incentives (2012)

No.	Project type	Project Company	Project Name
1	Passenger BEVs	Anhui Jianghuai Automobile Co., Ltd.	JAC’s fifth generation of pure electric car platform technology development project
2		Dongfeng Motor Corporation	Dongfeng small electric car technology development projects
3		Beijing Automotive Co., Ltd.	Beijing brand new platform pure electric car technology development project
4		Zhejiang Geely Automobile Co., Ltd.	Based on a new Imperial EC7 pure electric car technology development project
5		Chongqing Changan Automobile Co., Ltd.	Changan C206 pure electric vehicle technology development project
6	Passenger PHEVs	BYD Automobile Co., Ltd.	BYD new plug-in hybrids (Qin) technology development projects
7		China First Automobile Group Corporation	FAW Red Flag plug-in hybrid car technology development projects
8		Chery Automobile Co., Ltd.	Chery plug-in hybrid electric vehicle technology development projects
9		Great Wall Motor Company Limited	The new plug-in hybrid SUV Development Project
10		Shanghai Automotive Group Co., Ltd.	SAIC Roewe 550PHEV plug-in hybrid car technology development projects
11	Pure electric buses	Anhui Ankai Automobile Co., Ltd.	New models of pure electric bus technology development project

12		Dongfeng Automobile Co., Ltd. (Xiangyang)	Dongfeng city bus new energy technology development project
13		Shenzhen Wuzhou Dragon Motor Co.	Wuzhou Dragon New Energy Bus Technology Development Project
14	Plug-in electric buses	Hunan CSR Times Electric Vehicle Co., Ltd.	New energy bus technology development project
15		Zhengzhou Yutong Bus Co., Ltd.	Yutong Bus series products pure electric drive technology development project
16		Zhongtong Bus Holding Co., Ltd.	Plug-in hybrid and pure electric commercial vehicle technology development project
17	FCEV	Shanghai Automotive Group Co., Ltd.	SAIC Roewe 750 sedan fuel cell technology development project
18	Battery technology	Shenzhen BAK Battery Co., Ltd.	Lithium-ion batteries for electric vehicles key materials, monomers and module technology development projects
19		Universal Electric Vehicle Co., Ltd.	Vehicle lithium-ion battery technology development projects
20		CNAC lithium battery (Luoyang) Co., Ltd.	Electric vehicle battery technology development projects
21		Tianjin Lishen Battery Co., Ltd.	The next generation of battery technology development projects
22		Fujian Ningde era of new energy lithium-ion	Lithium-ion battery technology development projects
23		Shandong Heter Electronic Technology Co., Ltd.	Electric vehicle battery project

24		Green Power Co., Ltd. Weifang Vaillant	New energy automotive industry development projects in battery technology
25		OPTIMUM Battery Co., Ltd. of Shenzhen City	Shenzhen OPTIMUM power battery technology development projects

Data source: (*List of projects to be supported in the 2012 new energy vehicle technology projects*, 2012)

References:

Abuelsamid, S. (2010). Better Place expands Tokyo battery swap trials; taxis have changed packs 2,122 times already. Retrieved June12, 2013, from http://green.autoblog.com/2010/08/27/better-place-expands-tokyo-battery-swap-trials-taxis-have-chang/

Alan L. Porter, S. W. C., Alejandro Sanz. (2013). *Extending the FIP (Forecasting Innovation Pathways) Approach through an Automotive Case Analysis*.

Associates, A. (2013). Study Identifies Benefits and Potential Environmental/ Health Impact of Lithium-ion Batteries for Electric Vehicles. from http://www.abtassociates.com/newsreleases/2013/study-identifies-benefits-and-potential-environmen.aspx

Auto safety chief denies sitting on Chevy Volt warnings in heated hearing. (2012). from http://www.foxnews.com/politics/2012/01/25/highway-safety-chief-says-government-ties-to-gm-played-no-role-in-delay-chevy/

Bilotkach, V., & Mills, M. (2012). Simple Economics of Electric Vehicle Adoption. *Procedia-Social and Behavioral Sciences, 54*, 979-988.

CO_2 emissions from transport. (2013). http://data.worldbank.org/indicator/EN.CO2.TRAN.MT: The World Bank.

Collia, D. V., Sharp, J., & Giesbrecht, L. (2003). The 2001 National Household Travel Survey: a look into the travel patterns of older Americans. *Journal of safety research, 34*(4), 461.

Country analysis brief overview. (2012). http://www.eia.gov/countries/country-data.cfm?fips=CH: U.S. Energy Information Administration

Crist, P. (2012). *Electric Vehicles Revisited: costs, subsidies and prospects*.

Curtin, R., Shrago, Y., & Mikkelsen, J. (2009). Plug-in Hybrid Electric Vehicles. *Reuters/University of Michigan, Surveys of Consumers*.

Dedehayir, O. (2009). Bibliometric study of the reverse salient concept. *Journal of Industrial Engineering and Management, 2*(3), 569-591.

Dedehayir, O., & Mäkineif, S. J. (2008). Dynamics of Reverse Salience As Technological Performance Gap: an Empirical Study of the Personal Computertechnology System. *Journal of technology management & innovation, 3*(3), 55-66.

Dedehayir, O., & Mäkinen, S. J. (2011). Determining reverse salient types and evolutionary dynamics of technology systems with performance disparities. *Technology Analysis & Strategic Management, 23*(10), 1095-1114.

Dinger, A., Martin, R., Mosquet, X., Rabl, M., Rizoulis, D., Russo, M., & Sticher, G. (2010). Batteries for electric cars: Challenges, opportunities, and the outlook to

2020. *Boston Consulting Group*.

Electricity production. (2013). http://data.worldbank.org/indicator/EG.ELC.PROD.KH: The World Bank.

. *Financial incentives to technology innovation projects for automotive industry*. (2012). http://jjs.mof.gov.cn/zhengwuxinxi/tongzhigonggao/201210/t20121012_687400.html: Ministry of Finance of the People's Republic of China.

FuelCellToday. (2013a). Fuel and Infrastructure. Retrieved June12, 2013, from http://www.fuelcelltoday.com/about-fuel-cells/applications/fuel-and-infrastructure

FuelCellToday. (2013b). Transport. Retrieved June12, 2013, from http://www.fuelcelltoday.com/about-fuel-cells/applications/transport

Garthwaite, J. (2011). Lithium Ion Batteries Faulted for Jet Crash. from http://gigaom.com/2011/04/04/lithium-ion-batteries-faulted-for-jet-crash/

German, J. M. (2004). Hybrid Electric Vehicles. *Encyclopedia of Energy, 3*, 202-203.

. Global EV Outlook 2013-Understanding the Electric Vehicle Landscape to 2020. (2013). International Energy Agency: International Energy Agency.

Graham, R. (2001). Comparing the benefits and impacts of hybrid electric vehicle options. *Electric Power Research Institute (EPRI), Palo Alto, CA, Report, 1000349*.

Greene, D. L., Duleep, K. G., & McManus, W. S. (2004). Future potential of hybrid and diesel powertrains in the US light-duty vehicle market.

Hensley, R., Newman, J., & Rogers, M. (2012). Battery technology charges ahead. *McKinsey Quarterly*.

Hoyer, K. G. (2007). The battle of batteries: a history of innovation in alternative energy cars. *International Journal of Alternative Propulsion, 1*(4), 369-384.

Hughes, T. P. (1983). Networks of Power: Electrification in Western Society, 1880-1930, John Hopkins, Univ. *Press, Baltimore*.

Høyer, K. G. (2008). The history of alternative fuels in transportation: The case of electric and hybrid cars. *Utilities Policy, 16*(2), 63-71.

Jeeninga, H., van Arkel, W. G., & Volkers, C. H. (2002). Performance and Acceptance of Electric and Hybrid Vehicles. *Municipality of Rotterdam, Rotterdam, Netherlands*.

JENSEN, C. (2011). Fisker Recalling 239 Karma Plug-In Hybrids for Fire Hazard. from http://wheels.blogs.nytimes.com/2011/12/30/fisker-recalling-239-karma-electric-cars-for-fire-hazard/?_r=2

Karden, E., Ploumen, S., Fricke, B., Miller, T., & Snyder, K. (2007). Energy storage devices for future hybrid electric vehicles. *Journal of Power Sources, 168*(1), 2-

11.

Kizilel, R., Lateef, A., Sabbah, R., Farid, M. M., Selman, J. R., & Al-Hallaj, S. (2008). Passive control of temperature excursion and uniformity in high-energy Li-ion battery packs at high current and ambient temperature. *Journal of Power Sources, 183*(1), 370-375.

Koberg, D., & Bagnall, J. (1974). *The universal traveler: a soft-systems guide: to creativity, problem-solving, and the process of design*: W. Kaufmann.

Linked in Profile. (2013). 2013. http://nl.linkedin.com/pub/roberto-galante/9/776/725

. *List of projects to be supported in the 2012 new energy vehicle technology projects*. (2012). http://jjs.mof.gov.cn/zhengwuxinxi/tongzhigonggao/201212/t20121203_707706.html: Ministry of Finance of the People's Republic of China.

Loveday, E. (2010). Report: Mitsubishi working on battery swapping for transit buses, Better Place not involved Retrieved June12, 2013, from http://green.autoblog.com/2010/04/29/report-mitsubishi-working-on-battery-swapping-for-transit-buses/

MacCarley, C. A. (2000). *A Review of Battery Exchange Technology for Refueling of Electric Vehicles.* Paper presented at the Proceedings of SAE Future Car Conference 2000: Washington, DC.

Mak, H.-Y., Rong, Y., & Shen, Z.-J. M. (2012). Infrastructure planning for electric vehicles with battery swapping. *Available at SSRN 2022651*.

Markel, T., & Simpson, A. (2006). *Cost-benefit analysis of plug-in hybrid electric vehicle technology.* Paper presented at the 22nd International Electric Vehicle Symposium.

Matters, W. E., & Policy, E. (2010). The MIT Energy Initiative’s Symposium on Electrification of the Transportation System. *Electrification of the Transportation System*, 13.

Matters, W. E., & Policy, E. V. (2010). The MIT Energy Initiative’s Symposium on Electrification of the Transportation System. *Electrification of the Transportation System*, 13.

McKinsey, & Company, A. (2010). portfolio of power-trains for Europe: a fact-based analysis: Report.

McManus, W. (2003). Consumer Demand for Alternative Powertrain Vehicles. JD Power and Associates, Detroit, Michigan.

Morales-Espana, G. A. (2010). *Electric Vehicle Diffusion Exploring Uncertainties using System Dynamics.* (MSc.), Delft University of Technology, Delft.

Morgan, T. (2012). *Smart grids and electric vehicles: Made for each other?*

Mulder, K., & Knot, M. (2001). PVC plastic: a history of systems development and entrenchment. *Technology in Society, 23*(2), 265-286.

Nam, E. K., & Giannelli, R. (2005). Fuel consumption modeling of conventional and advanced technology vehicles in the Physical Emission Rate Estimator (PERE). *Assessment and Standards Division Office of Transportation and Air Quality US Environmental Protection Agency, EPA420-P-05-001*.

Narich, C., Stark, M., Schutz, M., Ubbink, P., & Noom, M. (2011). Changing the game: plug-in electric vehicle pilots.

Natkin, R. J., Xiaoguo, T., Boyer, B., Oltmans, B., Denlinger, A., & Heffel, J. W. (2003). Hydrogen IC engine boosting performance and NOx study. *SAE transactions, 112*(3), 865-875.

Nemry, F., & Brons, M. (2010). Plug-in hybrid and battery electric vehicles. Market penetration scenarios of electric drive vehicles: Institute for Prospective and Technological Studies, Joint Research Centre.

Nigro, N. (2011). *Plug-in Electric Vehicles Market: State of Play*: Pew Center on Global Climate Change.

Ogden, J. M. (1999). Developing an infrastructure for hydrogen vehicles: a Southern California case study. *International Journal of Hydrogen Energy, 24*(8), 709-730.

Ogden, J. M., Dennis, E., Steinbugler, M., & Strohbehn, J. (1995). Hydrogen energy systems studies. *final report to USDOE for Contract No. XR-11265-2*.

O'Keefe, M., Brooker, A., Johnson, C., Mendelsohn, M., Neubauer, J., & Pesaran, A. (2011). Battery Ownership Model: A Tool for Evaluating the Economics of Electrified Vehicles and Related Infrastructure.

Pesaran, A. (2010). Battery Ownership Model: A Tool for Evaluating the Economics of Electrified Vehicles and Related Infrastructure.

Phaal, R. (2002). Foresight Vehicle technology roadmap–technology and research directions for future road vehicles. *UK Department of Trade and Industry, URN, 2*, 933.

Plotkin, S., Santini, D., Vyas, A., Anderson, J., Wang, M., Bharathan, D., & He, J. (2002). Hybrid electric vehicle technology assessment: methodology, analytical issues, and interim results: Argonne National Lab., IL (US).

Porter, A. L., Cunningham, S. W., Banks, J., Roper, A. T., Mason, T. W., & Rossini, F. A. (2011). *Forecasting and management of technology*: Wiley.

Pritchard, E., & Zickefoose, P. E. B. (2005). HYBRID ELECTRIC SCHOOL BUS PRELIMINARY BUSINESS FEASIBILITY REPORT: Raleigh, NC: Hybrid Electric School Bus Program.

Ralston, M., & Nigro, N. (2011). *Plug-in Electric Vehicles: Literature Review*: Pew Center on Global Climate Change.

Reibnitz, U. v. (1987). *Szenarien-Optionen für die Zukunft*: McGraw-Hill.

Rhyne, R. (1981). Whole-pattern futures projection, using field anomaly relaxation. *Technological Forecasting and Social Change, 19*(4), 331-360.

Ritchey, T. (1998). *General morphological analysis.* Paper presented at the 16th EURO Conference on Operational Analysis.

Ritchey, T. (2006). Problem structuring using computer-aided morphological analysis. *Journal of the Operational Research Society, 57*(7), 792-801.

Romana, L. (2010). Potential Solutions for Electric Vehicles in Bus and Delivery Traffic.

Sakurambo. (2007). Diagram of a solid oxide fuel cell. Retrieved June12, 2013, from http://en.wikipedia.org/wiki/File:Solid_oxide_fuel_cell.svg

Sawhney, H., & Wang, X. (2009). Reverse Salients at the Meta‐System Level: The Case of Containerization. *Prometheus, 27*(2), 153-169.

Serra, J. V. F. (2012). *Electric Vehicles: Technology, Policy, and Commercial Development*: Earthscan.

Shurig, R. (1984). Morphology: A tool for exploring new technology. *Long Range Planning, 17*(3), 129-140.

Suh, N. P. (2001). *Axiomatic design: advances and applications* (Vol. 4): Oxford university press New York.

Takeishi, A., & Lee, K.-J. (2005). Mobile music business in Japan and Korea: copyright management institutions as a reverse salient. *The Journal of Strategic Information Systems, 14*(3), 291-306.

. *The announcement of energy conservation and new energy vehicle demonstration projects*. (2009). http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/200902/t20090205_111617.html: Ministry of Finance of the People's Republic of China.

. *The announcement of subsidies for private purchase of energy vehicles*. (2010). http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201005/t20100531_320528.html: Ministry of Finance of the People's Republic of China.

. *The announcement of the expansion of public services, energy-saving and new energy vehicle demonstration projects*. (2010). http://jjs.mof.gov.cn/zhengwuxinxi/zhengcefagui/201005/t20100531_320523.html: Ministry of Finance of the People's Republic of China.

. *The expansion of new energy buses demonstration cities*. (2012). http://jjs.mof.gov.cn/zhengwuxinxi/tongzhigonggao/201209/t20120917_683279.html: Ministry of Finance of the People's Republic of China.

Tom Hazeldine, S. K., Charlotte Brannigan, Matt Morris and Laura Deller. (2009). Market outlook to 2022 for battery electric vehicles and plug-in hybrid electric vehicles. AEA group.

Traction, D. G. (2011). Will Consumers Ride the Electric Vehicle Wave. *European Analysis (Deloitte Global Services Limited, 2011)*.

Xueqing, J. (2013). New energy vehicles await fuel injection, *China Daily*.

Zwicky, F. (1967). *The morphological approach to discovery, invention, research and construction*: Springer.