Alternative fuels in heavy-duty truck transport for a sustainable future

A study assessing the feasibility ranking of hydrogen, battery electric, biodiesel HVO and LNG powered trucks in European heavy-duty transport when a JIT/JIS supply chain strategy is applied.

VDL Nedcar

TU Delft

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MASTER OF SCIENCE

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by

Jur Haster

Student number: 4971876

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Graduation committee

Chairperson	: Prof. dr. G.P. van Wee, section Transport & Logistics
First Supervisor	: Dr. J.A. Annema, section Transport & Logistics
Second Supervisor	: Dr. E. Schröder, section Economics of Technology and Innovation
External Supervisors	: Ir. F. Henckens and Ing. T. Feld, VDL Nedcar

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On the 8th of February 2021, I started my thesis at VDL Nedcar. Here I received a warm welcome from all colleagues. Although, the COVID-19 pandemic was still ongoing, I was able to work fulltime at their office. This created the possibility for me to familiarize myself with their company and get a thorough understanding of their processes.

First, I want to thank Tristan Feld for his supervision and his willingness to be my neighbour at the office. His tips, tricks and contacts within the company helped me to complete this thesis. Moreover, I would like to thank Freek Henckens for facilitating and supervising this thesis. Despite, the hectic times, Freek always managed to make time for my questions without losing his critical view, which is appreciated. Furthermore, I would like to thank the graduation committee, especially Jan Anne with whom I had contact on a regular basis. During these contact moments, Jan Anne always made sure I worked towards a higher standard of quality by asking critical questions. At last, I would like to thank all colleagues of the SCE department at VDL Nedcar for their hospitality and helping me find my way at their company.

Jur Haster

Born, August 2021

Glossary

BET	Battery Electric Truck
BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle, also known as Hydrogen truck
FTL	Full-Truck-Loads
HRS	Hydrogen Refuelling Station
HVO	Hydrotreated Vegetable Oil
JIS	Just-in-Sequence supply chain
JIT	Just-in-Time supply chain
LNG	Liquefied Natural Gas
LSP	Logistic Service Provider
MCDM	Multi-Criteria Decision-Making
WOW	Warehouse-on-Wheels
ZEV	Zero Emission Vehicles

Summary

Since the last decade, climate change and environmental awareness has received increasingly more attention from politicians and companies. In order to preserve earth's climate, a lot has to be changed in current industry standards. In 2018, heavy-duty road transport was responsible for 680 million tonnes kg in transported commodities in the Netherlands (CBS, 2019). This resulted in 10.176 million tonnes of emitted CO_2 in the same year (CBS, 2020). As these transportation activities are a big part of the current pollution, there is a lot to be gained in this area. Therefore, industries are investigating to make their transportation activities more sustainable.

Large manufacturing plants often apply specific supply chain strategies in order to reduce waste. One of those wastes are warehousing costs. Just-in-Time (JIT) and Just-in-Sequence (JIS) are supply chain strategies that aim to reduce these costs (Bányai & Bányai, 2017). A JIT supply chain strategy refers to a strategy where commonly used parts are delivered at the plant when needed, therefore reducing storage capacity. A JIS strategy goes even further. When products are customizable, a JIS strategy ensures that the required parts are delivered in the sequence of production (Feld, personal communication, 2021).

Upon till now, a lot has been researched with regard to alternative fuels in heavy-duty transport, especially in the hydrogen and battery electric area. However, these studies often stay on a general logistics level. Specific concepts such as JIT and JIS may influence choices for alternative fuels due to more important time constraints such as a predefined and strict pearl chain[1] horizon. This could make Battery Electric Vehicles (BEVs) potentially less suitable, due to long recharging times. However, the impacts of these concepts on feasibility have hardly been researched. Therefore, this thesis aims to fill the knowledge gap that bridges the possibilities of alternative fuels (hydrogen, battery electric, biodiesel HVO and LNG) and a JIT/JIS supply chain strategy. In other words, the objective of this thesis is to provide an advice for companies in the manufacturing industry, which use a JIT/JIS supply chain strategy, how they can make their transportation activities more sustainable using alternative fuels. To achieve this results, data from a case study has been used. This case study is done at VDL Nedcar, which is an automotive manufacturer whose aim it is to implement a more sustainable logistics chain.

This translated to the following research question:

What are feasible alternative fuels in European heavy-duty transport when a JIT/JIS supply chain strategy is applied?

[1] Pearl chain: the sequence in which the type and configuration of vehicles to be produced is defined. This fixed period is often a couple of days. In VDL Nedcar's case 8 days (Renet, personal communication, 2021).

The first step in the process of assessing feasibility of alternative fuels was to create a conceptual model. This model is established by combining the findings of a literature study and acts as a "guideline" for other companies in the industry for the interviews and the data gathering to finally determine the feasibility ranking of alternative fuels within their specific case. The conceptual model is divided into two streams. Stream 1 determined the best suiting alternative fuel within this application using a more theoretical approach. Stream 2 explains a more practical view on how Logistics Service Providers (LSPs) see this transformation towards alternative fuels.

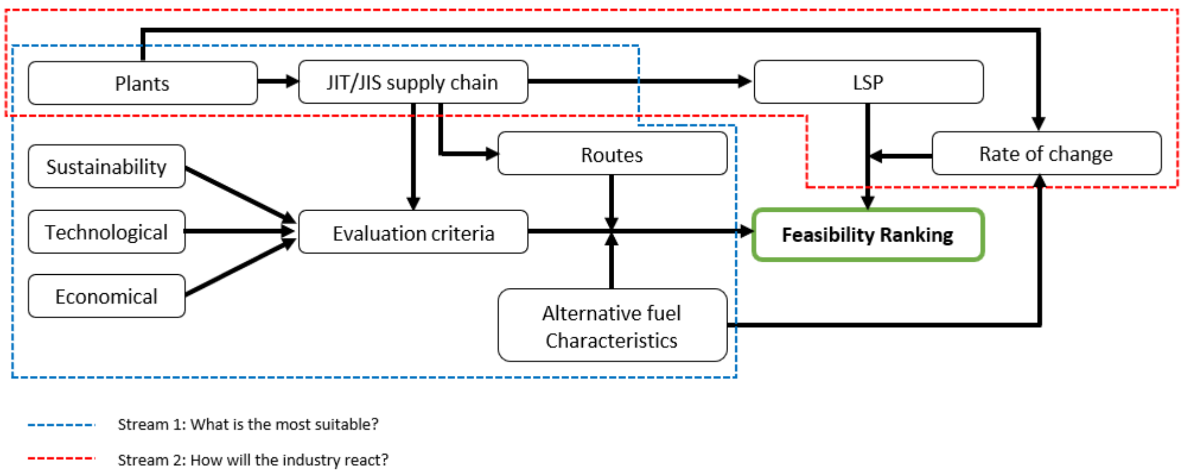

Figure 1: Conceptual model for the feasibility ranking of alternative fuels in a JIT/JIS supply chain

According to the conceptual model the feasibility ranking is dependent on three perspectives: (i) Sustainability (ii) Technological (iii) Economical. These general feasibility perspectives can be translated in specific and measurable evaluation criteria. The literature shows that the JIT/JIS supply chain characteristics influence criteria from all three perspectives, like transport time for example. Next, the selected criteria were weighted by performing a Best-Worst analysis. From this analysis became clear that in a corporate environment, costs is the most decisive factor. To put into perspective: costs were considered to be three times more important than Tank-To-Wheel emission reductions. Even though, green-house gas reduction was the incentive for conducting this research. To gain an understanding about the evaluation criteria that are selected and its weight distribution, figure 2 can be consulted. Here, the implications of a JIT/JIS strategy became clear. The transport times are heavily weighted in a JIT/JIS supply chain, where in other research transport times were barely considered. This is due to the principles of a JIT/JIS supply chain where truck arrivals are scheduled within half hour time slots (van Mierlo, personal communication, 2021).

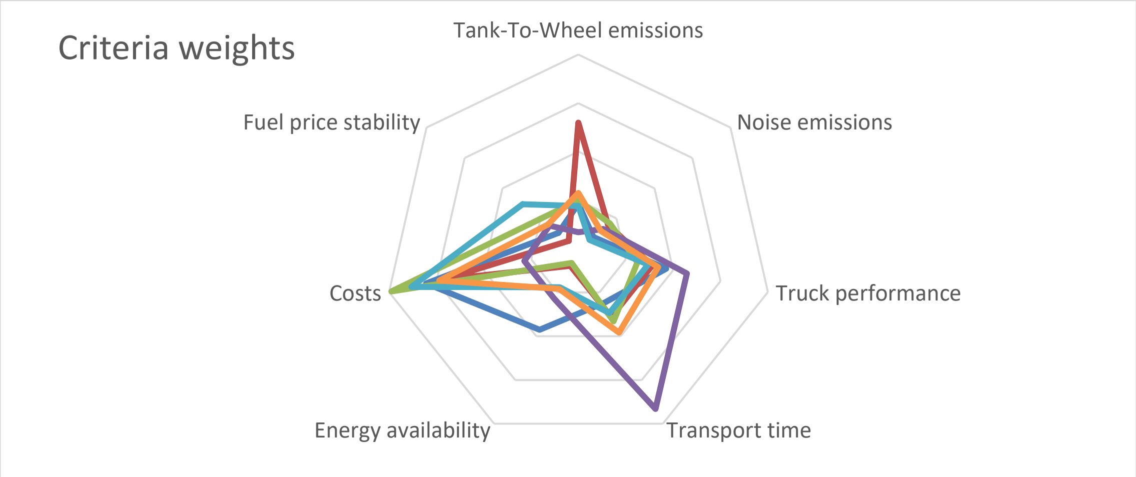

Figure 2: Evaluation criteria weight distribution

The literature study made it clear that some alternative fuel characteristics are highly dependent on the geographical location of the route. Therefore, in the conceptual model a connection has been made between the evaluation criteria, alternative fuel characteristics and the routes. Infrastructure, that determines transport times, is such characteristic. This is due to potential detours to make a route feasible. Furthermore, due to the same reasons, costs and Tank-To-Wheel emission are considered a route dependent criteria as well. Therefore, within the JIT/JIS supply chain of the case, eight routes were selected to evaluate the "scores" of alternative fuels. These scores are based on findings sourced from the literature study and are 2023 expectations. Multiplying these scores with their respective weights resulted in a weighted score which can be consulted in figure 3. In other words, these are the feasibility ranking results of stream 1.

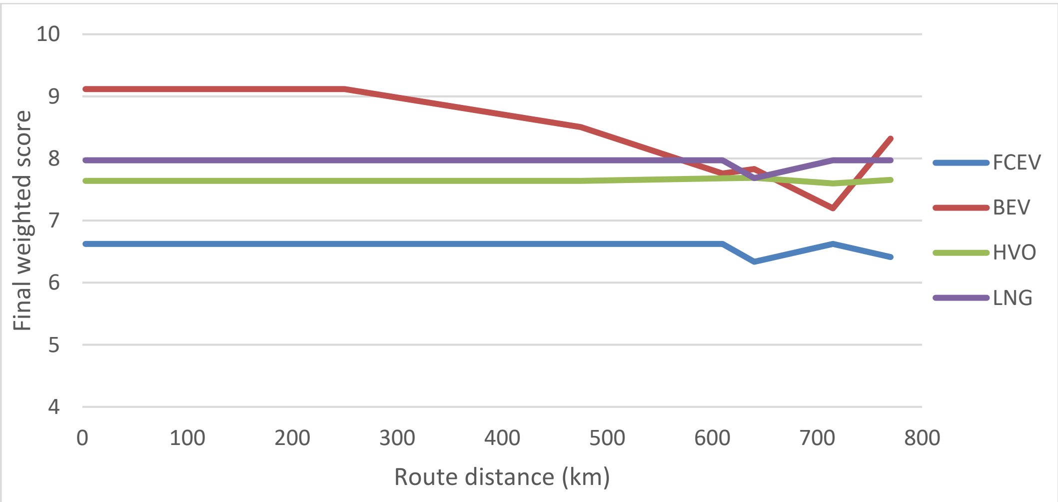

Figure 3: Average weighted scores with regard to route distances

One can clearly see the high feasibility ranking of Battery Electric Trucks (BETs). This can be explained by relatively lower additional costs. As that criteria is weighted the heaviest, this has a tremendous impact on the average score. However, as transport distances start to increase, the score decreases as expected. This can be explained by an increase in refuelling time and occasional detours. Nevertheless, there is an increase visible at 750 km mark. This is due to the requirement of an additional obligated break, which decreases the relative time losses. This is an important finding of this thesis: If BETs were able to bridge the transport distances of obligated breaks (360 km), time losses can be kept to a minimum. Furthermore, LNG and HVO perform exceptionally consistent. However, due to a significant increase in costs, their scores or feasibility rankings are slightly lower. Moreover, with regard to LNG should be noted that trips from the UK are less feasible as gaseous fuels are not allowed to use the Eurotunnel (Eurotunnelfreight, 2021). Furthermore, the refuelling infrastructure of HVO outside of the Netherlands is close to zero. Fortunately, HVO can be mixed with regular diesel to make routes feasible. At last, hydrogen performs well with regard to sustainability and technological related evaluation criteria. However, costs are the largest drawback. Fuel cost need to decrease with around 66% in order to become the best alternative fuel in a JIT/JIS supply chain. Fortunately, multiple sources state a future fuel costs decrease of more than 90%.

At this point, stream 1 of the conceptual model is completed. Stream 2 explains the way Logistic Service Providers (LSPs) see the transformation towards a sustainable truck fleet and what rate of adoption is likely to occur. In general, most LSPs were reserved regarding this transformation, especially with regard to BETs. This was mostly based on "gut feelings" fuelled by negative expectations. However, these negative views were also substantiated by experiments done by a LSP. In other words, there is a gap between the theoretical best (stream 1) and the practical view (stream 2). Fortunately, LSPs were relatively optimistic regarding LNG. Although there are still some large uncertainties, experience from the field seemed to be promising. In most cases, HVO is not considered as a feasible alternative. This is due to fact that HVO is relatively unknown by foreign companies. Moreover, Dutch companies explained high amount of uncertainties. At last, more progressive companies were exceptionally positive regarding hydrogen. One LSP even claimed to have their first hydrogen powered truck operational in 2025. However, these LSPs argued that experiences obtained by implementing a small LNG fleet are crucial to the widescale adoption of a large hydrogen fleet. This is due to a similar refuelling procedure.

All in All, using the theoretical model from stream 1, BETs seemed to be most feasible. However, according to the expectations in a wider timeframe, hydrogen seems to be a feasible alternative as well. This is due to the large fuel price reductions expected after 2023. Stream 2, was rather positive regarding LNG in the short-term and hydrogen in the long-term. Nevertheless, high amount of uncertainties and obstructions need to countered. In this process of implementing a more sustainable truck fleet, it is advised for companies, such as VDL Nedcar, to contribute to the development stage of alternative fuels. By implementing a couple of BETs on short routes (up to 15 km), plants are able to create the possibility for LSPs to gain experiences. By doing so, the gap between the two streams could be reduced. The same applies for LNG trucks: implementing a small fleet of LNG trucks in the short-term, provides the opportunity for LSPs to gain knowledge that can be used to eventually implement a large hydrogen fleet. On a final note, as costs is the most decisive criteria and alternative fuels are in general more costly, governments need to decide how financial incentives or subsidies are going to be structured as soon as possible, in order to make sustainability related objectives reachable. Up until now, these are still uncertain. This is crucial for companies in their transformation process.

Contents

1 Introduction

Since the last decade, climate change and environmental awareness has received increasingly more attention from politicians and companies. Both are looking for ways to address this issue across different sectors. In order to preserve earth's climate, a lot has to be changed in current industry standards. However, due to financial interests of companies, the change of this industry standard towards a more sustainable one, moves slower than required. In order to speed up this process, the Dutch government created an incentive for companies. This incentive involves a climate plan to meet European climate goals for the period 2021-2030. The main goal of this plan is related to the reduction of green-house gasses, CO_2 for example. This European agreement aims to reduce CO_2 emission by 50% in 2030 compared to 2016 for business related kilometres and involves an introduction of CO_2-tax from 2023 and onwards for industries in general as an financial incentive (Ministerie van Economische Zaken en Klimaat, 2020).

In 2018, heavy-duty road transport was responsible for 680 million tonnes kg in transported commodities in the Netherlands (CBS, 2019). This resulted in 10.176,0 million tonnes of emitted CO_2 in the same year (CBS, 2020). It is estimated that the commercial transport sector is responsible for roughly 20% of the total green-house gas emissions in Europe (European commission, 2016). Within this 20%, heavy-duty road transport accounts for roughly 25% of all transport emissions. In other words, 5% of the total green-house gas emissions originate from heavy-duty road transport (Singh, et al., 2015). As these transportation activities are a big part of the current pollution, there is a lot to be gained in this area. Therefore, industries are investigating to make their transportation activities more sustainable.

There are several options to reduce these emissions, a potential reduction can be found by using different energy carriers (fuels) and improving vehicle efficiency. Conventional diesel is the most used energy carrier in heavy-duty transport nowadays (97%) (Singh, et al., 2015; Westaway, 2009) and is therefore considered an industry standard. Fortunately, innovative alternative fuels like electric and hydrogen trucks are being developed. In order to stay well below a 2°C increase in global average temperature compared to pre-industrial levels, a green-house gas reduction of 80-95% is needed in 2050 compared to 1990 (UNFCC, 2018). However, there are large obstacles on the road and innovations in this area have a long way to go. Shell CEO Ben van Beurden stated these concerns as: 'Transporters who want to move a heavy freight electrically over a large distance are currently faced with the choice: do I transport my cargo, or do I transport the batteries? Because both are still not workable' (van Dijk, 2018).

Large manufacturers often apply specific supply chain strategies in order to reduce waste. One of those wastes are warehousing costs. Just-in-Time and Just-in-Sequence are supply chain strategies that aim to reduce these costs (Bányai & Bányai, 2017). A Just-in-Time supply chain strategy refers to a strategy where commonly used parts are delivered at the plant when needed, therefore reducing storage capacity. A Just-in-Sequence strategy goes even further. When products are customizable, a Just-in-Sequence strategy ensures that the required parts are delivered in the sequence of production (Feld, personal communication, 2021) (see figure below).

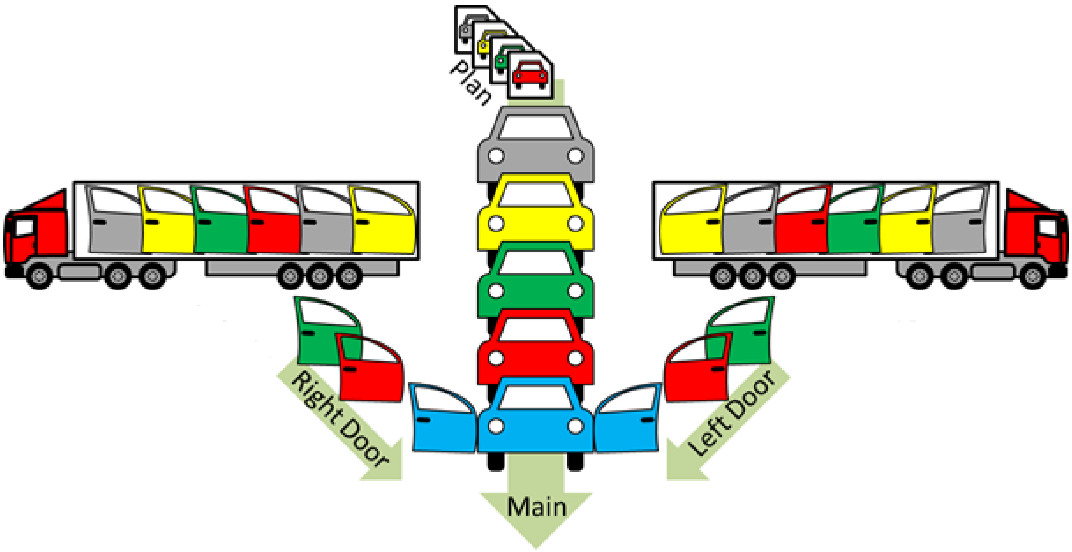

Figure 4: Just-in-Sequence supply chain strategy (Roser, 2021)

Upon till now, a lot has been researched with regard to alternative fuels (see chapter 3), especially in the hydrogen and battery electric area. However, these studies often stay on a general logistics level. Specific concepts such as Just-In-Time (JIT) and Just-In-Sequence (JIS) may influence choices for alternative fuels, due to more important time constraints such as, a predefined and strict pearl chain[2] horizon. This could make battery electric vehicles potentially less suitable, for example. However, the impacts of these concepts on feasibility have hardly been researched. Therefore, this study aims to fill the knowledge gap that bridges the possibilities of alternative fuels and JIT/JIS supply chain strategies. In order to do this, a concrete case will be used to evaluate the problem using real and accurate data regarding supply routes. The case involves VDL Nedcar, which is a contract car manufacturer located in Born (L) in the Netherlands. Currently, they are building the BMW X1, MINI Countryman (PHEV) and the MINI Convertible for BMW Group. In 2023 the contract between VDL Nedcar and BMW Group will be terminated. Therefore, to enhance their market position, they want to stay ahead of the competition with regard to sustainability to attract new customers (Feld, personal communication, 2021). One idea is to make the transportation of parts to the factory more sustainable. However, as VDL Nedcar uses a JIT/JIS supply strategy for most of their processes, they need a more thorough research in order to be able to make their business more sustainable. Therefore, they asked to research promising alternative fuels in order to make their heavy-duty transportation activities more sustainable when a JIT/JIS supply chain strategy is applied.

[2] Pearl chain: the sequence in which the type and configuration of vehicles to be produced is defined. This fixed period is often a couple of days. In VDL Nedcar's case 8 days (Renet, personal communication, 2021).

1.1 Problem definition

There is an abundance of information available regarding alternative fuels from existing scientific research as well as grey literature (see chapter 3). However, these studies often stay on a too general level and is hard to link with specific logistic processes, such as JIT/JIS. For example, it is expected that these strategies demand high reliability and consistency due to time sensitivity as a delayed delivery could cause a line stop resulting large production loses and costs. Therefore, to prevent such events, it might result in more requirements with regard to technological boundary conditions. This is not well researched in existing literature and therefore companies, similar to the case study (VDL Nedcar), struggle to make their transportation activities more sustainable despite the high demand for this transition.

Furthermore, in the existing literature, alternative fuels are often individually researched rather than compared to each other. Therefore it is hard to conclude which alternative fuel is the most feasible solution within a certain timeframe and under certain conditions. Adding this to the knowledge gap related to the specific supply chain strategy, an opportunity for research arose.

1.2 Scope definition

This thesis is based on a previous study performed during the preparation for the master thesis course (MOT2004). That study has been structured as an funneling process where alternative fuels are evaluated. That study resulted with four of the most promising alternative fuels within heavy-duty transport which will be used in this thesis. These are: hydrogen (FCEV), battery electric (BEV), biodiesel HVO and LNG (Haster, 2021).

Furthermore, the scope will be limited to tractor and semi-trailer combinations due to the commonly used Warehouse-On-Wheels (WOW) strategy, which goes hand-in-hand with a JIT/JIS strategy (see chapter 3). The case (chapter 1.4) involves a company in the automotive industry, here mega-trailers are used as standard mode of transportation. These trailers imply the use of low-deck tractors. These combinations are built to maximize load volume. This will be taken into account in this research, but will not be limited to.

1.3 Research Objective and Questions

To address the issues as discussed above, the main goal of this research is to: provide an advice for companies in the manufacturing industry, which use a JIT/JIS supply chain strategy, how they can make their transportation activities more sustainable using alternative fuels.

To achieve the objective as described above, a research questions must be compiled. This research question will be answered at the end of this thesis and will provide the advice this industry requires.

What are feasible alternative fuels in European heavy-duty transport when a JIT/JIS supply chain strategy is applied?

In order to provide an answer to the main question, nine sub-research questions need to be answered.

1. From which perspectives is it important to evaluate feasibility in a corporate organisation?
2. What evaluation criteria are used in the literature to evaluate alternative fuels?
3. What are the characteristics of each alternative fuel powered truck?
4. What is JIT/JIS and who is involved?
5. What are conceptually important feasibility criteria for alternative fuels when a JIT/JIS supply chain is applied?
6. What are the weights of the evaluation criteria within the case study?
7. What are representative supplier routes within the case study?
8. How do the alternative fuels perform when applied to the routes?
9. How do logistic service providers see the transformation towards sustainability?

1.4 Case description

VDL Nedcar is a contract vehicle manufacturer. That means they build cars for other brands. In the past, they built cars for DAF, Volvo and Mitsubishi. After an acquisition by VDL they started to build different models for BMW Group. Now, they are building the BMW X1, MINI Convertible and the MINI Countryman (PHEV). Unfortunately, their contract with BMW Group will be terminated in 2023 (Feld, personal communication, 2021). In order to attract new customer(s), they are seeking to enhance their market position. Their strategy is to do this by making their company more sustainable. To make it tangible, they established the goal to reduce their overall green-house gas emissions by 25% in 2025 (Feld, personal communication, 2021). As their transportation activities are large contributor to these emissions, they want to convert to an alternative fuel for their inbound logistics. Due to the expiring contract with BMW group and the expiration of the contract with logistic service providers they aim for a solution that can be implemented in the short-term (2023). By doing so, they strengthen their market position by advocating themselves as an environmental friendly business in order to attract new customers. Moreover, they are interested in long-term (2030) solutions as well, due to the Paris Agreement (Feld, personal communication, 2021).

The automotive industry mostly relies on a Just-In-Time (JIT) and a Just-In-Sequence (JIS) supply chain strategy. These strategies involve a minimized warehousing strategy by using a strict planning of deliveries. This can be up to a couple of hours before parts need to be at the assembly line. This will be further elaborated in chapter 3. VDL Nedcar has seven logistics service providers driving in such JIT/JIS strategy. Which is expected to result in an average of 270 Full-Truck-Loads (FTL) per week, which involves a total transported volume of over 21.500 m^3 per week, in the year 2021 (Feld, personal communication, 2021). Which is extraordinary low compared to previous years due to a dip in car sales caused by the Corona virus.

1.5 Thesis outline

This thesis is structured in the following way: first, in chapter 2, the methodology is described. In this chapter will become clear how the research question will be answered and what methods that are used. In chapter 3, a literature study will result in a conceptual model that describes how to companies could determine feasibility regarding the scope. In this conceptual model, the perspectives in which such innovations need to be evaluated, are described. Next, the evaluation criteria which are used in other research, are stated. Furthermore, the fuel characteristics are described and at last, a JIT/JIS supply chain is explained. This conceptual model is used to structure the remaining chapters of this thesis. Chapter 4 will determine the evaluation criteria that are applicable to the scope of the research and a restructured evaluation criteria model will be built. Chapter 5 will examine the weight associated to the new evaluation criteria model and will explain the implications of the JIT/JIS strategy on those weights. In chapter 6, representative routes from the case study will be determined, which makes it possible to score the alternative fuels accordingly. The next chapter will determine how logistic service providers see the transformations towards alternative fuels. In chapter 8, the thesis will be discussed and the connection with the master program MOT will be explained. Furthermore, the scientific and managerial contribution of this thesis will be elaborated. Next, chapter 9 will draw a conclusion with regard to this thesis. At last, chapter 10 will provide both short-term and long-term recommendations for companies such as VDL Nedcar.

2 Methodology

This section discusses the methodology that is used to answer all research question. In order to provide a clear insight in the iterative process of this research, a visualization of the steps and methods that are followed can be consulted in figure 5. This is called the research design.

2.1 Research design

The figure below explains the steps that have been taken during this research. Here, all sub-research questions are assigned to a "box" in which the method is stated as well. Here, one can see that the results of a sub-research question initiates or defines the baseline for the next. Besides that, this figure defines which sub-results are sourced from the case study. Furthermore, this research design defines four distinct research methods:

1. Literature review
2. Semi-structured interviews
3. Desk research
4. Best-Worst Method

This will be further elaborated in the upcoming sections.

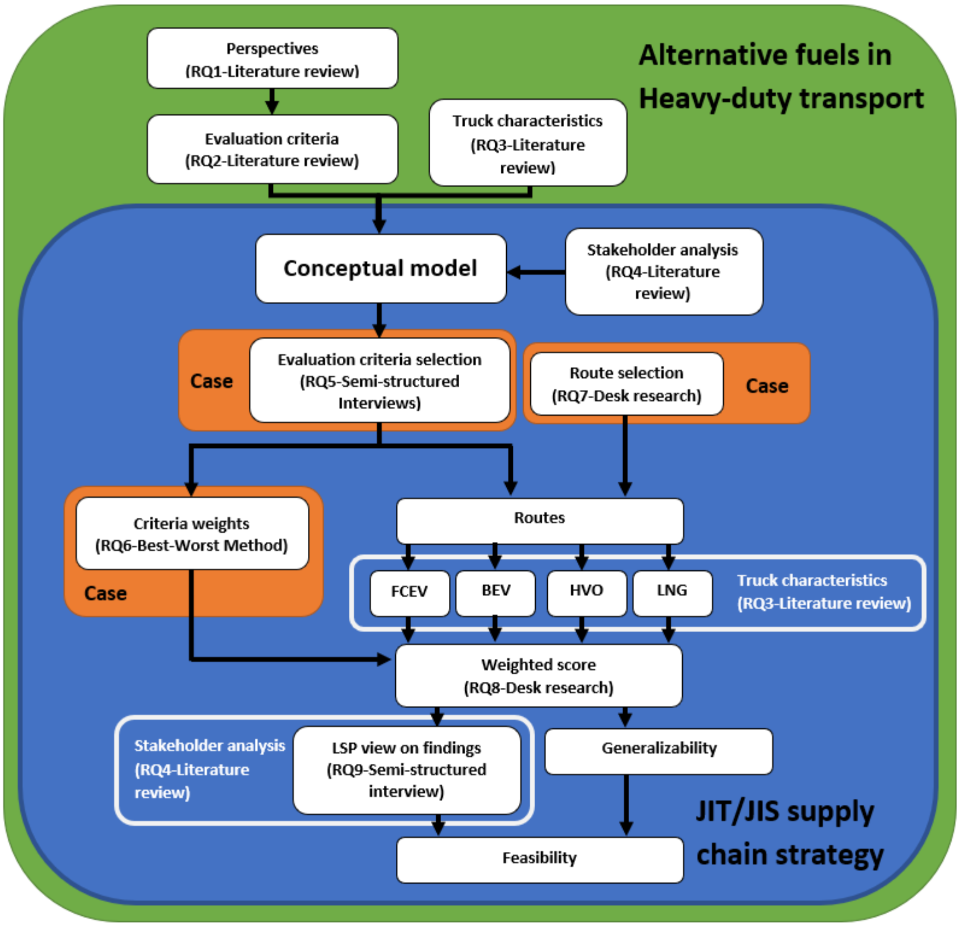

Figure 5: Research design

In order to obtain a well substantiated result, the following steps are taken: (i) the perspectives in which corporate environments define feasibility is determined. This is done by performing a literature study on how experts advocate this to be done. (ii) Within these perspectives, evaluation criteria that are used for other alternative fuel applications are found. This is done by a literature study as well. These two steps are a preparation for answering RQ5 (step iii). Here, experts within the case were asked which evaluation criteria from the literature are applicable for their specific application. Moreover, these interviewees were free to add evaluation criteria as well. The next step (iv) of this process was to determine the weights of these criteria. Here, experts from multiple departments within the case were asked to complete the BWM and provide substantiation. Next (v), representative routes within the case are determined. (vi) Combining these routes with the alternative fuel characteristics, a nominal score has been determined. However, these nominal scores neglect the relative importance of these criteria. (vii) Multiplying these nominal scores with the criteria weights determines the best suitable alternative fuel within a JIT/JIS supply chain. However, this theoretical result on its own is useless without the connection with a practical orientated approach. Therefore, in the next step (viii) these theoretical results are evaluated against the view of logistic service providers.

2.2 Case study

First, will be explained why sub-RQ 5, sub-RQ 6 and sub-RQ 7 will be answered by extracting information from a case study and why this is important.

Case studies allow for profound insights on multiple practical processes that are confined in time and space (Verschuren et al., 2010). Yin suggests, in a research performed in 2017, that case studies are relevant methods when research questions seek to explain current circumstances where situations require in-depth descriptions. The essence of this case study research is to obtain data that is actually representable for the industry as discussed, get a thorough understanding of requirements and limitations within companies and how experts foresee possibilities. Therefore, the objective of this case study is to ensure applicability of the results within the context of the industry.

Critical to the research is a well-defined case to be studied and set limits (Yin, 2017). For this research, the relevant situation to analyse refers to the feasibility of alternative fuels in heavy-duty transport within Europe when a JIT/JIS supply chain strategy is applied. The company that is used in the case study (VDL Nedcar) implemented these supply strategies and is seeking to make there inbound logistics more sustainable. By using the expertise and data of VDL Nedcar and their logistic partners, a reliable and valid conclusion can be drawn. The risk that the results are hard to generalize across the industry might seem to be present. However, most vehicle manufactures apply the same strategy within their supply chain. Therefore, it is expected that the results should be applicable to others as well. This will be explained in chapter 9.

2.3 Data sources

2.3.1 Literature review – RQ1, RQ2, RQ3, RQ4

A literature review is a useful method to get an understanding of existing literature. This is useful as it helps to identify and explore innovations with regard to alternative fuels and provides a background of JIT/JIS supply strategies. A drawback of literature reviews is that one can only find information about subjects that have been researched before. As the possibilities of alternative fuels within the context of the case study have not been researched, it is difficult to gather information directly related to the topic. Fortunately, this is the literature gap that this thesis aims to fulfil.

After the scope of the research was defined, the search for articles and other relevant literature began. This has been done by searching in the academic database GOOGLE Scholar and the TU Delft repository. Besides that, also non-scientific and so called "grey literature" has been explored. This grey literature mainly consists of governmental publications of (new) laws and publications made by truck manufacturers.

This research started by analysing the main topic and identifying relevant selection criteria to structure the literature study. Table 1 represents the search criteria used with regard to the topic. The initial search criterion list and its synonyms was not as extended at the start of the search as it is presented below. This is due to the iterative process of doing research, were along the way new insides are gained. However, it was required to keep close to the initial criteria to preserve its relevance. In the search for literature is departed from the studies found regarding alternative fuels in heavy-duty transport. Therefore, an inclusion criteria for selecting the remaining literature was a direct link to these initial search criteria with the exception of the JIT/JIS related literature.

Table 1: Initial search criteria

Search criteria	Synonyms or related keywords
Alternative fuels	Hydrogen, FCEV, battery electric vehicles/trucks, Biodiesel, HVO, liquefied natural gas, LNG
Just-In-Time / Just-In-Sequence	JIT, JIS
Heavy-duty transport	Heavy-duty truck, commercial fleet, truck transport
Green-house gas emissions	CO_2 emission, environmental pollution
Multi-criteria decision-making	Best-worst method, Delphi method, AHP, ANP, hierarchical hesitant fuzzy linguistic model

2.3.2 Semi-structured interview – RQ5, RQ9

This case study research has been collecting qualitative data by means of conducting semi-structured interviews, which are according to Yin (2018) helpful in providing explanations and insights. These involve one-to-one interviews conducted by a rather flexible approach on one general topic, which can be covered in detail. Furthermore, semi-structured interviews are used to verify, validate and complement the literature review results. With the help of expert interviews, the literature review results will be discussed and evaluated more in-depth. This method is suitable as new technologies are often uncertain and experts in the field can give their opinion and vision about how this might develop in the future (Goluchowicz & Blind, 2011). The interviews are semi-structured based on the questions formulated from the literature review results and possible knowledge gaps. The semi-structured interviews are used as a guideline for the conversation. This is done to focus the interview on the important topics without deviating as much. Nevertheless, general comments are also encouraged.

The interview process consists of the following steps: Experts are approached via e-mail or telephone for the interview. A general description of the thesis will be given, and the specific area of their expertise is highlighted. Next, in preparation of the interviews, the information package is sent that allows them to prepare. At last, after the interviews, an interview report is created and sent for verification to the interviewees before the information is used.

Interviewees were selected based on their expertise within their respective companies. For selecting the evaluation criteria, three interviewees were used. These three were considered to be crucial in the transformation process towards alternative fuels, as they are the main decision-makers with regard to inbound logistics of VDL Nedcar. It should be noted that, due to time constraints of this thesis, a limited amount of three interviews were performed regarding this sub-research question. When determining evaluation criteria weight an additional two experts were chosen. These two experts are a bit more involved with operations which resulted in a larger support base for the findings from this specific department. At last, four Logistic Service Providers (LSPs), who are involved with JIT/JIS, were selected based on their operating regions (i.e. South Germany or the UK). Within these companies the interviewees were chosen based on their knowledge regarding alternative fuels or their acquaintance with VDL Nedcar.

Table 2: Overview of interviewees

Personal information			Purpose		
Name	Company	Function	Evolution criteria	Criteria weight	View on transformation
T. Feld	VDL Nedcar	Supply Chain Engineer	X	X	
L. Lindelauf	VDL Nedcar	General Manager Supply Control	X	X	
F. Henckens	VDL Nedcar	General Manager Supply Chain Engineering	X	X	
H. van Mierlo	VDL Nedcar	Team leader Transport Control		X	
L. Heiligers	VDL Nedcar	Team leader Inbound Logistics		X	
J. Everts	Ewals cargo care	General Manager Trucking			X
A. Schlüter	Duvenbeck	Head of Service and Communication			X
T. Ribalet	Transimeksa	Head of EU Fleet Operations			X
S. Butz	Elflein	Key Account Manager Transport			X

Because the number of interviews is low and the background of the interviewees includes a wide range of functions, the interviews are not coded. During the interviews, notes were taken and all relevant answers have been summarized. These summaries of the interviews are approved by the corresponding interviewee. As will be described below, the Best-Worst Method will be used to determine the criteria weights. Although this method is not necessarily considered a semi-structured interview, it is arguably an interview. Therefore, the interviewees used for the BWM are stated in table 2 as well.

2.3.3 Desk research – RQ7, RQ8

A desk research will be conducted to process information and data. Here, mostly plain quantitative data has been processed in order define representative routes in the case of RQ7. Regarding RQ8, it involved determining the scores using quantitative data.

2.3.4 Best-Worst Method – RQ6

In order to determine to what extend each criteria affect the outcome of feasibility, a Multi-Criteria Decision Analysis (MCDA) has been used. A Best-Worst Method (BWM) is such method and is used due to its structured way of collecting data, its high reliability, efficiency and user-friendliness (Rezaei, 2015). This method required several criteria of input to function properly. As mentioned earlier, a literature study in combination with interviews has been conducted to determine these criteria within the scope as described in previous sections.

This method is chosen because (i) it has a high reliability and consistency when compared to other MCDM methods (Rezaei, 2015). (ii) It specifies a structured methodology for the respondents to provide the pairwise comparison data, through its use of the most and least important factors as reference points. (iii) It requires less pairwise comparisons than other MCDM methods like Analytical Hierarchy Process (AHP) (Rezaei, 2015). In other words, by using this method the time intensity and the degree of difficulty for decision-makers within the case, is limited. What might increase the reliability of the results.

The Best Worst Method (BWM) is a way of reaching a decision when several significant alternatives exist. In order to express the significance, a number of criteria are drawn up. In this way, the BWM is part of Multi-Criteria Decision-Making (MCDM). As stated by Jafar Rezaei (2015), "An MCDM problem is a problem where a number of alternatives (options) need to be evaluated with respect to a number of criteria (attributes) in order to (i) select the best alternative, or (ii) rank all the alternatives, or (iii) sort the alternatives into a number of classes". When referring to the 'best' or 'worst' criteria, it implies the most important and the least important factor respectively. The aim of this is to make a selection between the alternatives in order to arrive at the most desired outcome. The most desired outcome will therefore have to be assigned a certain value. In order to reach this conclusion, five steps have been taken:

1. In the first instance, a set of (n) criteria have been determined.

$$\mathrm{c1}, \dots, \mathrm{cn}$$

2. The criteria that is the most important (best) and the least important (worst) have been indicated.
3. In order to give value to the best reference criterion, a scale range of 1 to 9 has been assigned to the best in order to compare it to the other criteria. A 9 indicates that the best criterion is the most preferred over the other criterion and 1 indicates the same preference. This results in a Best-to-Others vector (BO). Where A_{Bj} indicates the preference of the best criterion B over criterion j.

$$A_B = (A_{B1}, A_{B2}, \dots, A_{Bn})$$

The meaning of the numbers 1-9:
1: **Equal** importance
2: Somewhat between Equal and Moderate
3: **Moderately** more important than
4: Somewhat between Moderate and Strong
5: **Strongly** more important than
6: Somewhat between Strong and Very strong
7: **Very strongly** important than
8: Somewhat between Very strong and Absolute
9: **Absulutly** more important than

Figure 6: Best-Worst scale (Rezaei, 2015)

4. In order to give a value to the best reference criterion, a scale range of 1 to 9 has been assigned to the other criteria in order to compare it with the worst. A 9 indicates that the criterion is the most preferred over the worst and 1 indicates the same preference as the worst. This results in a Others-to-Worst vector (OW)

$$A_W = (A_{1W}, A_{2W}, \dots, A_{nW})^T$$

This resulted in the following findings:

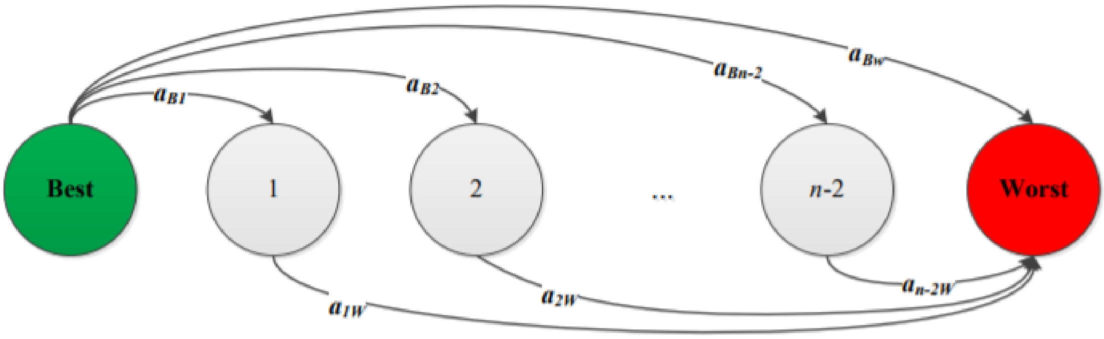

Figure 7: Visualization of the pairwise comparison (Rezaei, 2015)

5. As a final step, the weights of all criteria are determined. For this purpose, a min-max optimisation model has been formulated by Rezaei (2015). This, model is incorporated in a predefined Excel solver (retrieved from bestworstmethod.com (2021)) and is used to derive the following vector W:

$$W = \begin{matrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{matrix}$$

In order to obtain an usable outcome, close interaction with the experts was required. What emerges from these steps is that the BWM uses a pairwise comparison method between the best and worst alternatives and the other criteria.

Using the findings from several sub-questions, a performance matrix has been established. Here, “A” defined the alternative fuels and ”c” states the evaluation criteria from the perspectives as mentioned earlier.

$$P = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \cdots & c_n \end{array} \\ \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1} & P_{m2} & \cdots & P_{mn} \end{bmatrix} \end{array}$$

Multiplying matrix P and vector W from the Best-Worst analysis, the utility values (V) are determined.

$$V_i = \sum_{j=1}^{n} W_j P_{ij}$$

This is the actual score of each alternative fuel and created the opportunity to draw a well substantiated conclusion.

2.4 Type of results

Quantitative results

Adjusting the performance matrix to the specific route profiles should results in a new performance matrix specific to certain route characteristics, geographical location or distance for example. Multiplying this with the weights of the Best-Worst analysis results in quantitative data that provides a more theoretical advice for the most suitable alternative fuel for this specific supply chain.

Qualitative results

A more qualitative result came from the semi-structured interviews that assessed the rate of adoption of alternative fuels by logistic service providers. These qualitative findings provide a more realistic or practical view on the feasibility of alternative fuels.

3 Conceptual model

In this chapter, a conceptual model will be established (see figure 9). This model will be used to determine the feasibility of the alternatives fuels as described before. Furthermore, the conceptual model provides an insight how factors in a feasibility assessment relate specific for situations similar to the case. In other words, similar companies in the automotive industry are able to use this model to determine the feasibility ranking of alternative fuels specific for their needs by "filling in the blanks". Moreover, this conceptual model acts as a guideline for interviews and data gathering as well.

To conclude, in this chapter will be explained how the conceptual model is build, how it interrelates and background information regarding each factor will be provided.

3.1 Perspectives

First of all, the perspectives, in which this research will be conducted, needs to be determined. This founds the base from which this research will depart.

Manufacturing industries, such as the automotive industry, have an important role in the transformation towards a more sustainable way of doing business (Gaziulusoy et al., 2012). Eco-labelling, environmental management, environmental legislation, extended producer responsibility, corporate social responsibility (CSR) and guidance for social sustainability are examples of activities that enable this transformation. Several incentives are the driving forces in this process. An improved corporate image, increased profitability, energized employees, are such driving forces (Hallstedt et al., 2012). Furthermore, more demanding consumer requests, stricter legislation and resource constraints also contribute towards a faster transformation within the industry to operate in a more sustainable way (Hallstedt et al., 2012). However, as Ivanova et al. (2017) states: "One needs an advanced indicator of competitiveness". Which refers both to economic and technological assessments. Moreover, it is emphasized by Zimmermann et al. (2020) that when assessing technology or innovations to enhance sustainability it is important to assess the economic viability upfront using a detailed techno-economic assessment.

The problem statement as communicated by the automotive industry, confirms the need for performing this research from the above described perspectives. However, it is emphasized that these perspectives are approached through a corporate view.

To summarize, in this section the following sub-research question is answered:

RQ 1: From which perspectives is it important to evaluate feasibility in an corporate organisation?

There are three perspectives found that are important to perform this research. These are:

1. **Sustainability**: To what extend can an alternative fuel contribute towards a more environmental friendly way of transportation?
2. **Technological**: To what extend is an alternative fuel technological feasible on defined routes?
3. **Economical**: What costs are associated with the alternative fuels?

3.2 Evaluation criteria from the literature

Within these perspectives there are numerous evaluation criteria that could determine feasibility. Literature has been studied to assess how other research evaluated alternative fuels in other applications. The literature often involved a multi-criteria decision-making method, but was not limited to. It should be noted that the evaluation criteria found in the literature sometimes are strongly related or influence each other. Nevertheless, all criteria found are listed in the table 3.

It can be concluded that studies have used a wide range of evaluation criteria to assess alternative fuels within their respective applications. These applications range from buses in Germany to light-duty vehicles is China.

RQ 2: What evaluation criteria are used in the literature to evaluate alternative fuels?

Table 3: Evaluation criteria from the literature

	Criteria	Yavuz et al., 2015	Anderhofstadt et al., 2019	Parker et al., 1997	Melendez, 2006	Tsita et al. 2012	Maimoun et al., 2015	Sehatpour et al. 2017	Tzeng et al. 2005	Mukherjee 2016	Osorio-Tejada et al. 2017	Liang 2019	Number of occurrences
Sustainability	Greenhouse gas emissions	x	x			x		x	x	x	x	x	8
	Social welfare impact	x				x		x					3
	Noise emission		x						x	x	x		4
	Ecological impact manufacturing and recycling		x										1
	Well-to-Tank emissions		x										1
	Tank-to-Wheel emissions		x				x						2
	Well-to-Wheel emissions		x										1
	Life-cycle emissions						x						1
Technological	Reliability	x	x								x		3
	Performance (weight, load length)	x	x		x				x	x	x		6
	Refueling infrastructure	x	x	x	x		x	x			x	x	8
	Refueling time	x	x	x						x	x		5
	Safety	x	x					x					3
	Driving range	x	x						x				3
	Perceived quality/comfort	x							x	x			3
	Transport time								x	x			2
	Energy availability					x			x	x			3
	Manufacturers' warranties		x										1
	Service quality of manufacturer		x		x								2
	Downtime			x									1
	Power density/ fuel efficiency						x	x	x	x		x	5
Economical	Purchase costs	x	x		x		x	x		x	x	x	8
	Operational costs	x						x		x			3
	CO2 Tax										x		1
	Financial grants/incentives		x		x			x					3
	Current fuel costs		x	x		x	x				x	x	6
	Future trend fuel costs		x										1
	Service and maintenance costs		x	x					x		x		4
	Taxes and insurance		x										1
	Depreciation/ resale value		x										1
	Conversion/ implementation costs			x	x	x		x	x				5
	Fuel price stability						x	x					2

3.3 Alternative fuel powered truck characteristics

An important part of the feasibility assessment are the characteristics of each alternative fuel. Therefore, an extensive literature review has been conducted to provide background information with regard to the individual fuels. This section is a summary of the literature study which can be consulted in the appendix. In other words, here the characteristics of the four alternative fuels are described that found the baseline findings of this research and provides an insight in the actual innovation itself.

All in all, in this section hydrogen, battery electric, HVO and LNG will be discussed with regard to the perspectives as elaborated in section 3.1. This provides the required information to answer the upcoming research questions.

3.3.1 Hydrogen

Hydrogen vehicles, or Fuel Cell Electric Vehicles (FCEV), are similar to electric vehicles. They are driven by electric engines. However, they store energy in a different way. Hydrogen vehicles store energy in fuel cells containing hydrogen. Production is done by electrolysis. In this process, water is split into hydrogen and oxygen. This process only consumes electrical energy, making these vehicles as clean as the energy used during electrolysis (Yavuz et al., 2015). Many studies evaluated the possibilities of hydrogen powered transportation. Most of them argue that hydrogen is good alternative when boundary conditions are met (Oostdam, 2019). Moreover, many experts consider hydrogen vehicles the future of transportation. A study done by van der Zwaan et al. (2013) predicts that hydrogen will become the dominant transport fuel during the second half of 21st century. Hydrogen vehicles have all the benefits of electric vehicles and, in addition, have a longer driving range without refuelling. However, whether or not this fuel can contribute towards a sustainable way of transportation before 2030 is yet to be determined, especially when a JIT/JIS supply strategy is applied.

Hydrogen: a sustainability perspective

Hydrogen can be combined with oxygen in the electrochemical reactions of a fuel cell to produce electricity, a clean, versatile energy carrier. Fuel cells produce electricity with a potential efficiency of 60%. The electricity can be directly converted to motion (Crabtree & Dresselhaus, 2008). In a Tank-To-Wheel analysis hydrogen powered trucks emit no green-house gasses. During the conversion of this energy carrier towards kinetic energy, the only residual product is water (Crabtree & Dresselhaus, 2008).

Hydrogen: a technological perspective

In Europe, there are strict regulations regarding truck dimensions. These dimensions are fixed in height, width and length. The total length includes the tractor maximum length, trailer maximum length as well as the maximum total length of the combination of tractor and trailer (Evofenedex, 2021). These rules make it challenging to incorporate the components in the tractor as one needs, among others a fuel cell, a battery and an electric motor (Oostdam, 2019). Optimally, these components need to be placed in the trucks without compromising load lengths. However, mounting a fuel tank in a hydrogen truck is challenging. Given the low density of hydrogen, the fuel tank will be relatively large. It is estimated that roughly 1 m^3 stores 39 kg of hydrogen at 700 bar. At 300 bar, the same amount of kilograms will use approximately 1,6 m^3 (Oostdam, 2019). Furthermore, it is estimated that fuel tanks only have an efficiency of 80%-90% (Peters et al., 2021; Oostdam, 2019). This is due a minimum required pressure inside the tanks.

In current hydrogen trucks concepts, there are three possibilities for mounting a hydrogen fuel tank (Oostdam, 2019).

1. Placing the hydrogen tanks directly behind the cabin. This requires multiple smaller tanks of approximately 5 kg which are stacked vertically. Nikola has adopted this concept and released a capacity of 34 kg (Nikola, 2019).
2. Placing hydrogen tanks in the side pods. This implies that the tanks are located between the first and second wheel axles. Diesel trucks mount their diesel in tanks here as well.
3. Placing the tanks in the trailer. This concept is a prototype truck that has been developed by VDL for the project Waterstofregio 2.0 (Oostdam, 2019). The project consists of creating a 44-ton electric tractor semitrailer with a hydrogen range extender. The truck can drive 100 kilometres on its battery, with the hydrogen range extender the driving range can be extended to 400 kilometres (Oostdam, 2019). However this would compromise load lengths significantly.

Research shows that hydrogen trucks (tractors) weigh around 14 tons, which is similar to diesel powered trucks (Transport and Environment, 2020). In other words, no additional tractor weight is expected. Even if it does so, Zero Emission Vehicles (ZEV) get exemption for additional load weight up to 2.000 kg. This would imply that load weights are not compromised. ZEVs and near-ZEVs may exceed obligated gross vehicle weight limits by an amount equal to the difference of the weight of the (near-)ZEV powertrain and the weight of a comparable diesel tank and fuel system. This additional weight can be up to 2.000 kg. A ZEV is defined as a vehicle that produces no “criteria pollutant”, toxic air contaminant, or greenhouse gas emissions when stationary or operating conditions. A near-ZEV is a vehicle that uses zero emission technologies, uses technologies that provide a pathway to zero emission operations, or incorporates other technologies that significantly reduce vehicle emissions (Alternative Fuels Data Center, 2021).

However, Peters et al. 2021 explains that, concerning weight issues, due to the exchange of ICE and gearboxes by electric drivetrains leaves only 243 kg for the fuel cell system. For the calculation of the achievable driving range, they assumed the following efficiencies: 60% fuel cell system, 97% power electronics, and 95% electric motor. These assumptions would imply a tank-to-wheel efficiency of 55%. An assumed tank weight of 557 kg will allow maximum range between 338 and 646 km (Peters, et al., 2021). Again, the main challenge for hydrogen storage systems is the small volumetric energy density, as stated by Peters et al. Furthermore, a study that assessed fuel cell systems, determined that the weight of hydrogen (tested at 5,6 kg capacity) is only 5% of the total tank weight at 700 bar. In a 350 bar configuration, this would be 6% of the total tank weight (Hua, et al., 2010). This results in a total tank weight (filled) of 112 kg at 700 bar. Extrapolating this linear, would mean a full tank weight 1.600 kg at 80 kg hydrogen capacity. However, real world applications are expected the weight less, due to more efficient tank shapes.

A few companies are developing hydrogen powered trucks. Unfortunately, the manufacturing process of these vehicles is in its early stages. Hyzon Motors is such company. They claim that their heavy-duty trucks has 500 KW (Hyzon motors, 2021). Nikola advocates similar power outputs (Nikola, 2019). These values are similar to common diesel configurations as well. Hyzon Motors claims a 400-600 km range in their 50 ton heavy-duty applications (Hyzon motors, 2021). However, In EU a maximum of 40 ton is allowed during standard transportation activities. This might lead to longer driving ranges on European roads. It should be noted, these values are expectations advocated by the companies who are about to sell these vehicles. Road test might conclude different driving ranges, as driving style etc. might influence these values.

Another technological aspect to consider is the fact that a Hydrogen Refuelling station (HRS) needs to “buffer” between refuelling cycles. That means that a pump needs to build up pressure for 20 to 30 minutes before a next vehicle is able to refuel (H2Platform, 2021).

Hydrogen: an economical perspective

It seems that investment costs are a large obstacle for logistic service providers when it comes to hydrogen powered trucks. This is because hydrogen trucks require twice as much investments as comparable diesel trucks. In the table below an overview is provided of current and future CAPEX.

Table 4: CAPEX values of hydrogen truck in euro. * grey literature

	Current CAPEX	Future CAPEX	Year
(Oostdam, 2019)	442.000	257.000 - 335.000	-
(Moultak et al., 2017)	300.000	207.000	2030
Hunter & Penev, 2019)	492.000	184.000	2040
(Vijayagopal & Rousseau, 2019)	316.000	175.000	2050
(Hyzon motors, 2021) *	285.000	178.000	-
(Cleantechnica, 2021) *	321.000	-	-

The table above shows a wide spread of values. In order to provide usable results, the average current CAPEX will be calculated, which is an average of 359.000 euro. Assuming a residual value of 50.000 euro over a 6 year period (Oostdam, 2019) and an average annual driving distance of 125.000 km, this would results in an euro/km of 0,41. HYZON motors claims a lifespan, in driving distance, of 700.000 miles, which is +/- 1.125.000 km (Hyzon motors, 2021). This would result in 0,27 euro/km. Which is a significant difference when driving long distances.

As hydrogen trucks do not emit green-house gasses in a Tank-To-Wheel analysis, they are exempted from future CO_2 tax. Furthermore, as of February 2021 the Dutch government announced new subsidy regulations for Zero Emission Vehicles above a curb weight of 4.250 kg (Rijksoverheid, 2021A). These regulations involve a financial incentive to test ZEV in practise. For this incentive the

Dutch government allocates 11 million euro for companies to get started with these test. How this exactly relates to individual companies or trucks is difficult to determine. Especially, when converted to euro/km.

Fuel costs strongly depend on the market size with respect to fuel demand. A significant share of the fuel cost consist of capital expenditures for production and storage facilities, involving Fuel transportation and the refueling station itself (Peters, et al., 2021). The size of a refuelling station strongly influences the price of hydrogen, because of economy of scale effects. As the hydrogen price is currently fixed to 10 euro/kg and there are only a few examples of fully utilized Hydrogen Refuelling Stations (HRS), it is difficult to determine the refuelling cost for the future (Oostdam, 2019). Oostdam states that the price of the refuelling station is expected to decrease as the utilization and capacity of a HRS increases. He states that it is estimated that the price could decrease to 1,00 euro/kg or less. According to Weeda (2019), it can approach 0,50 euro/kg if fully utilized and 1,00 euro/kg using a more conservative prediction. This is confirmed by other research as well (McKinsey, 2010). Converting this to a cost per km, using an energy consumption of 13 km/kg, it would results in 0,77 euro/km when currently implemented. However, fuel costs might trend towards 0,08 euro/km or lower.

Maintenance costs are hard to predict as no hydrogen trucks are commercially available yet. Nevertheless, as there are fewer parts in hydrogen truck, it is expected that maintenance intervals will be lower (Oostdam, 2019). To provide an insight, Hyzon Motors claims that maintenance on their hydrogen trucks will cost 0,11 euro/km (Hyzon motors, 2021)

3.3.2 Battery electric

It is commonly known that electric vehicles are more environmental friendly than the internal combustion engine used for diesel and gasoline applications. However, this type of vehicles have some limitations. Batteries for example, are not efficient enough when assessing power outputs per associated weight. Therefore, power outputs or driving ranges are limited without compromising load capacity. The electricity used in these vehicles can be generated from fossil fuels and renewable sources, such as wind and solar power. A third option is electricity generation through nuclear plants.

Research shows that electric vehicles emit only 66% of greenhouse gasses compared to combustion engines in a well-to-tank study (Yavuz et al., 2015). Furthermore, research done by Notter et al. in 2010 states that the pollution caused by battery production is relatively low compared to the benefits from the operational phase. Nevertheless it is emphasised that charging should be done by renewable sources.

Research advocates that electric vehicles could become a feasible solution. However, at the current rate of innovation it can only have a small contribution to the climate goals of 2030 (Huismans, 2018). In order to become a feasible solution within this time frame, electric vehicles need to overcome some large boundary conditions. Such as, battery performance or recharging infrastructures. Furthermore, existing research discussed this technology with regard to general transportation activities without focussing on specific supply chain strategies or other applications.

Battery electric: a sustainability perspective

Battery Electric Vehicles (BEV) do not emit green-house gasses when driving. In other words, in a Tank-To-Wheel analysis a 100% reduction in emitted green-house gasses compared to diesel powered trucks can be obtained. Therefore, battery electric vehicles, just like hydrogen powered vehicles, are called Zero Emission Vehicles (ZEV). Which are heavily promoted by governmental organisations and environmental initiatives.

Battery electric: a technological perspective

Looking at technical graphs of DAF CF, which are commercially available in battery electric configurations, load lengths are equal to diesel configurations (DAF, 2021). Here, the batteries are stored between the first two axles, It should be noted that the DAF CF as discussed has a 220 km driving range. The Tesla Semi truck, which has a driving range of approximately 800 km (Tesla, 2021), is not able to carry standard 13,6 m long mega trailers. This is due governmental restriction on maximum dimensions, which is in most countries of the European Union 18,75 meter (Evofenedex, 2021). Evaluating technical drawings of the Tesla Semi, a load length of approximately 1 meter will be lost. There are other examples of battery electric trucks, such as Volvo FE and the Mercedes-Benz EActros, however these are rigid trucks. This means they have more space between the axles to accommodate additional batteries to obtain an extended driving range. As discussed before, this research will focus on a tractor-trailer combination as this combination is used in a JIT/JIS strategy combined with a Warehouse-On-Wheels (WOW). Furthermore, it is important to note that the trucks as discussed are not a low-deck configurations, meaning that the mega trailers commonly used in the automotive industry cannot be hauled by these tractor configurations due to height restrictions.

It is often claimed that BEVs need to account for reduced load weight capacity due to the significant weight of the onboard battery system. Depending on the battery pack's energy density and capacity, this is often to be the case, particularly with respect to modern day’s battery technology (Transport and Environment, 2020). However, the additional weight due to the onboard battery pack can be compensated by the additional ZEV weight allowance, which is 2.000 kg, from replacing a conventional diesel engine with an zero emission drivetrain, such as battery electric drivetrains. Net payload losses are found in the range of 0 to 1.350 kg (Transport and Environment, 2020). However, in these calculations, battery pack weight is expected to be 3.616 kg where, other literature state 5 to 8 metric tons (Hyzon motors, 2021). Furthermore, literature is not consistent when using energy consumption at the wheel. These values range from 1,15 kWh/km to 1,6 kWh/km (Transport and Environment, 2020; Hall, 2019).

Commonly used trucks in long-haul transportation often have a power of 300 kW or more. However, real world examples such as the DAF CF electric only has a power of 210 kW (DAF, 2021), which is a substantial decrease. However, when hauling heavy cargo, torque is more important than power. Electric vehicles are commonly known for the excellent torque outputs. In heavy-duty trucks, this is no exception.

Tesla (2021) claims that their battery electric truck has a driving range up to 800 km. This is a significant increase compared to other battery electric trucks, especially when only considering tractor configurations. Again, the DAF CF Electric, which has a claimed range of 220 km, involves a driving range reduction of approximately 93% compared to similar diesel trucks. This means that, when driving at an average speed of 80 km/h, every 165 minutes the driver needs to recharge for at least 75 minutes. Although drivers need to rest every 4,5 hours for 45 minutes (Rijksoverheid, 2021B), it is considered a large burden. Especially when recharging infrastructure is limited or when recharging stations only have low power outputs. This would result in detours or longer recharging times.

Looking beyond the scope of tractor configurations, the rigid configuration of the Volvo FL Electric claims a driving range of 300 km with a battery capacity of 300 kWh. Which is 50 kWh less than the DAF CF Electric. However, as the Volvo has a rigid configuration, maximum load weights are limited. Hence, the relative increase in efficiency.

Battery electric: an economical perspective

The conditions for Battery Electric Trucks (BETs) have drastically changed since 2010. In that year, lithium-ion battery prices were around 900-1.200 euro per kWh (Wolfram & Lutsey, 2016) including an energy density of approximately 110 Wh/kg. In 2018, prices decreased with a factor of around four and energy densities have at least doubled. In other words, batteries are cheap and dense enough to be considered as viable for powering trucks (Earl et al., 2018). These trends in reduced costs and improvement in energy density has led to, and been driven by as well, a rapid increase in passenger electric vehicles, electric urban buses, and the emergence of heavy duty trucks (Earl et al., 2018). Following from a study done by Earl et al. in 2018, he stated the following: Before analysing the total CAPEX, it is worth mentioning the underlying battery price. Indeed, a large uncertainty when analysing the economic feasibility of battery electric trucks is the price per kWh of the battery. Allocating the entire purchase cost of the Tesla Semi to cover only the cost for the estimated 1000 kWh large battery, would suggest a battery cost of 150 euro per kWh. This can be confirmed by cost predictions made by (Wolfram & Lutsey, 2016; Moultak, Lutsey, & Hall, 2017). It should be noted, that this price is a gross overestimate, ignoring the cost of the other components of the truck and profit margins. Alternatively, the price difference between the two models can be considered, assuming that the price difference is attributable only to the battery size. Comparing the 475 km model to the 800 km model, there is a price difference of approximately 25.000 euro. This would result in a battery price of around 70 euro per kWh. Which is a price that approaches optimistic 2030 battery price expectations. The actual price is probably somewhere within this range of findings, and is estimated to be around 100 euro per kWh by Earl et al. (2018).

Fuel costs is a sensitive parameter in the cost calculation. On the one hand, the current diesel cost of around 1,10 euro per litre (Europa-vrachtwagens, 2021) applicable to logistic service providers is known with high certainty. Unfortunately, the electricity cost that will eventually be charged for recharging electric trucks is more uncertain. Today, the EU average industry rate is 0,12 euro/kWh whereas Tesla superchargers for cars are currently priced at 0,24 euro/kWh (Earl et al., 2018). This should be put in the context of the Shell supercharger charging 0,55 euro/kWh and Tesla promising 0,06 euro/kWh (Earl et al., 2018), what implies a wide range of prices. When assessing these costs, the EU industry average with the option of supercharging should be considered. As can be seen, the cost of electricity will determine the cost competitiveness of battery electric trucks in the EU (Earl, et al., 2018).

For conventional diesel trucks maintenance is quite extensive since they have many moving parts and usage causes a lot of wear. Fortunately, battery electric trucks require less maintenance and repairs compared to conventional diesel vehicles (Huismans, 2018). According to Onat et al. (2015), maintenance costs for a BEV is approximately 65–80% compared to an equivalent diesel engine due to fewer components and moving parts, as well as lower maintenance requirements for electric motors. Maintenance of electric vehicles includes the possibility of replacing the battery after its life-time as well. Other component on trucks, such as chassis and motors, tend to have longer life-cycles, this fact is often overlooked but should be accounted for as well (Huismans, 2018).

Considering maintenance and repair costs from an impact assessment (Maibach & Sutter, 2006) from the European Commission. They assume costs of 12.500 euro per year for internal combustions engines, such as diesel engines. It is estimated that battery electric trucks account for half of that, due to the much simpler drivetrain as described before. This is in-line with Stewarts & Dodsons (2016) findings, who use this reduction as well. However, they mention that there is a large variation of reported maintenance costs. This is substantiated by Józwicka (2016) as well. All in all, research done by Earl et al. (2018), shows maintenance costs of 0,10 euro/km.

3.3.3 Biodiesel HVO

The biodiesel name and its variants, HVO for example, are not well used in scientific and grey literature. There are contradictories and misconceptions when this “biofuel” is discussed and named. From the most credible sources, the findings are stated below.

Biodiesel can be produced with two different types of materials. First, Soy, oil palms and rapeseed are commonly used crop types to produce biodiesel (Yavuz et al., 2015) which is called generation 1. Second, production through biological wastes such as cooking oil or animal fat is called generation 2. This can be acquired from households and industrial facilities. The main difference is that generation 1 is made of edible resources and generation 2 is made of waste (Luque, et al., 2008). Therefore, generation 1 is not considered as a viable alternative fuel due to an already existing global food shortage. Generation 2, includes a fuel type called Hydrotreated Vegetable Oil (HVO). HVO has similar characteristics as diesel. Therefore, truck manufactures, like Volvo and Mercedes-Benz, are building diesel engines that can run on HVO without any modifications. Therefore, HVO is considered a promising alternative fuel.

Biodiesel or biodiesel-diesel blends could contribute to a more sustainable way of heavy-duty transport as well (Graham et al., 2008). However, to what extent is not clear. Besides that, limitations or boundary conditions in the adoption process are not well researched and should be well defined in order to evaluate this. These studies could help in comparison test between different alternative fuels as well. Again, in existing research the link between specific supply chain strategies, such as JIT/JIS, and biodiesel applications is missing.

Biodiesel HVO: a sustainability perspective

According to the literature, scientific test have been done to assess green-house gas emission of biodiesel HVO in a wide range of applications with promising results. Unfortunately, grey literature seems to be misleading as they often state that a CO_2 reduction is possible up to 90% in the case of HVO100 (OrangeGas, 2021; DAF, 2021). Although this can be true in a Well-To-Wheel analysis, this is not possible in Tank-To-Wheel analysis. This due to the fact how you allocate emission, as one can consider it as a residual product.

HVO can be mixed with conventional diesel. This can be done in a wide range of mix ratios, from 20% HVO (HVO20) up to 100% HVO (HVO100) which is pure HVO. Existing refuelling stations often offer HVO20 and HVO100. However, there are non-commercial examples of variable mix refuelling stations (Goodfuels, 2021). According to Peters et al. (2021), HVO blends up to 30% still comply with DIN EN 590.

An American research investigated potential Tank-To-Wheel emission reductions in heavy-duty applications in the USA (Karavalakis et al., 2016). HVO100 showed average Tank-To-Wheel reductions of around 33%. Other research stated similar findings with an average potential reductions in a Tank-To-Wheel analysis between 30% and 35%, using HVO100 (Kuronen & Mikkonen, 2007; Sugiyama et al., 2011).

Biodiesel HVO: a technological perspective

HVO can be used in most conventional diesel trucks without any mechanical modifications to the truck. Therefore, both load length and load weight are not affected by the implementation of this alternative fuel. This means the threshold for the adoption of this fuel is fairly low. Besides that, when HVO is blended with EN 590 diesel fuel, the blend meets EN 590 specification until the lower limits of a volumetric density of minimum 820 kg/m^3 in the summer and 800 kg/m^3 during the winter. This limit is often present at a mix rate of about 30% of HVO and 70% of diesel fuel (Kuronen & Mikkonen, 2007).

Furthermore, a research done by Sugiyama et al. in 2011, states that the volumetric heating value of HVO is 5% lower than diesel, creating the concern that torque might decrease at full load. It was found that the same torque and the same brake specific energy consumption could be obtained with HVO even at the same indicated value of injection duration as diesel fuel (Sugiyama et al., 2011). This is due to an increased injection quantity of HVO and similar heating values are obtained. The results show that, despite its lower volumetric heating value, HVO does not result in lower torque in full load operation (Sugiyama et al., 2011). Moreover, as a result of an optimized engine calcification, HVO is capable of improving partial fuel consumption and full-load torque. These results indicate that HVO has beneficial fuel characteristics when applied in diesel engines (Sugiyama et al., 2011). To conclude, performance wise, a HVO powered truck has similar characteristics as a diesel configuration.

As stated by Kuronen & Mikkonen (2007), the mass based heating value of HVO is higher than that of conventional diesel fuel. Therefore, mass based fuel consumption will usually be lower for HVO. They state, the mass based fuel consumption was 1.2-1.9 % lower with HVO100 compared to regular diesel. This is confirmed by CO_2 measurements at the tailpipe. However, the volumetric fuel consumption was 5-6% higher with HVO100 due to a difference in densities (Kuronen & Mikkonen, 2007). To conclude, because of a lower density volumetric fuel consumption is slightly higher when engines are driven on HVO rather than conventional diesel. When 10-30 % HVO is mixed with diesel the difference in volumetric fuel consumption are very low (Kuronen & Mikkonen, 2007). This means that, due to higher volumetric fuel consumption, driving range decreases accordingly. In other words, the driving range is estimated to be equal to diesel or up to 5,8% less with regard to equal tank sizes, depending on mix ratio.

Biodiesel HVO: an economical perspective

A HVO powered truck is in essence a normal diesel truck. Therefore, initial investments are equal to a diesel equivalent. Therefore, lowering the financial threshold for adopting this fuel. Besides that, due to the similarities to diesel, maintenance costs are expected to be around 0,18 euro per km, which is equal to diesel powered trucks. However, fuel costs are expected to increase. With total fuel costs of 0.50 euro per km (DCB Energy, 2021), there is an 8 cent increase with respect to this aspect.

3.3.4 LNG

LNG, like CNG, is a natural gas and is therefore considered a fossil fuel. Natural gas is considered the cleanest fossil fuel and can be mixed with up to 100% renewable methane. The overall motivation for using natural gas in heavy-duty transport is the reduced dependency on crude oil it offers and the use of different countries for energy supply (Peters, et al., 2021). Often the drivers for implementing natural gas in transport are emission reductions and energy security.

Engine technologies for natural gas vehicles can be divided in to three groups: (i) spark ignition (SI) engines, (ii) dual fuel (DF) engines, and (iii) high pressure direct injection (HPDI) engines. However, only HDPI engines are applicable when using LNG as a sole fuel, which is most suitable for heavy-duty trucks (Peters, et al., 2021).

There are no large manufacturers that offer this technology in personal vehicles (Yavuz et al., 2015). Nevertheless, there are production trucks built with LNG engines (Vermeulen et al., 2017), such as Volvo or DAF. Therefore, this type of fuel might have some potential. Nevertheless, research still needs to confirm or deny its potential, especially within the scope of the case study.

LNG: a sustainability perspective

A research, performed by TNO, tested emissions of a heavy-duty LNG truck (Vermeulen, 2019). They took a Volvo FH 420 LNG, which was introduced in 2018. This truck uses a so called HPDI technology and LNG storage. The results of this vehicle were reflected against older results from six diesel trucks from 2013. Measurements of the greenhouse gasses were performed. The results stated a reduction of 19% in greenhouse gas emissions for an average long-haul trip compared to the diesel baseline from 2013. For highway operations, the difference was even higher, which was up to 23% (Peters, et al., 2021). Furthermore, a Tank-To-Wheel assessment has been performed, by Dunn et al. (2013), of the first-generation HPDI engine based on emissions analysis during transient and steady-state cycles. Dunn et al. explains that they did not perform a well-to-wheel analysis due to uncertainties regarding upstream emissions. During these tests, they found a reduction of 22,9% of CO_2 compared to similar diesel applications. The emissions found at the exhaust, mainly consisted of CO_2.

In grey literature, Volvo stated CO_2 emission reductions, using their LNG application, of 20% (Volvo, 2021). This is similar to the Iveco Stralis Natural Power (IVECO, 2021) and Scania's Natural gas application with 410 HP, which has a driving range of 1600 km with two tanks (Scania, 2021). The motor is driven by pure natural gas using a spark ignition system. According to Scania, the engine emits up to 15% less CO_2 than a comparable diesel motor (Peters, et al., 2021). It should be noted, that these specifications are published by the truck manufacturers. Therefore, these findings can provide an indication but should be labelled as less reliable.

LNG: a technological perspective

The volumetric efficiency of LNG is 1,7 times lower than diesel. In other words, 1 liter of diesel will be replaced by 1,7 liters of LNG when other parameters are equal (Smajla et al., 2019). When driving range are kept similar to diesel, this would result in a 70% increase of fuel tank volume. Therefore, running the risk of reduced load lengths.

LNG powered trucks can be regularly seen on the road. In other words, there are real world applications of this type of propulsion. IVECO offers a LNG powered truck with 460 HP and 2.000 Nm (IVECO, 2021), which is similar to diesel configurations. Furthermore, Volvo offers two different LNG configurations of their Volvo FM, one with 420 HP and one with 460 HP (Volvo, 2021). Again this is similar to common diesel trucks. Assuming a 557 kg tank capacity, Peters et al. (2021) claim ranges of almost 1.700 km. However this resulted in a loss of load weight of around 500 kg (Peters et al., 20221). Smajla et al. (2019) states a fuel cycle of 950-1.200 km between refueling stations.

IVECO Stralis Natural Power mounts two LNG tanks between the first and second axle what makes it possible to achieve a driving range of 1600 km (IVECO, 2021). However, IVECO builds a low-deck configuration, as used in the automotive industry, as well. This low-deck tractor has a maximum range of up to 1.150 km (IVECO, 2021). Nevertheless, this decrease is sufficient for modern day long-haul transportation. Furthermore, Volvo build LNG powered low-deck trucks as well. They claim a driving range of up to 1.000 km (Volvo, 2021). At last, no load weight losses are mentioned In the specification sheets of both manufacturers.

LNG: an economical perspective

Westport Fuel Systems (2021), state an additional CAPEX of 40.000 euro for an LNG vehicle with HPDI technology compared to diesel configurations. The incremental price as stated by Westport is confirmed by the 35.000-50.000 euro estimations done by Anderhofstadt and Spinler (2019).

In 2019, the Dutch government announced an incentive for LNG. They announced that for the years 2020 and 2021, transport companies receive 0,187 euro per kilogram of LNG. This is directly compensated at the refueling station (Volvo, 2021). Furthermore, in Germany, there is an incentive as well. This so called “MAUT-exemption” determines that LNG powered trucks are not obligated to pay MAUT, which is a German tax. Depending on truck-trailer combination weight, this can result in fuel price savings up to 0,187 euro per kilometer (Volvo, 2021). However, Peters et al. (2021) state that if the energy tax reduction for natural gas does not apply in the future, LNG will become less attractive. Moreover, if LNG would be taxed similar to diesel on a carbon basis, no possibilities for financial savings are possible by switching to LNG (Peters et al., 2021).

A study concerning yearly fuel cost savings, when converted to LNG, concluded potential fuel cost saving between 13.863 and 19.029 euro per year when a LNG drivetrain is used (Americas Commercial Transportation Research, 2012). Similar findings have been stated by Smajla et al. in 2019. On average, they state a reduction in fuel costs of LNG powered trucks of around 48% less than diesel trucks. According to these cost expectations, the payback period is less than three years (Smajla et al., 2019). Other research shows payback times between 3 and 6 years (Anderhofstadt & Spinler, 2019; Peters et al., 2021). This includes the increased maintenance costs of 20% as advocated by Smajla et al. (2019).

3.3.5 Conclusion of alternative fuels

In this section the following sub-question is answered. By doing so, these findings can be used as a baseline for a more in-dept research for the specific application as discussed.

RQ 3: What are the characteristics of each alternative fuel powered truck?

In the literature review above, one can find the characteristics of hydrogen powered trucks (FCEV), Battery Electric Trucks (BET), Biodiesel HVO and LNG powered trucks. From the findings it becomes clear that each alternative fuel has specific characteristics and consequences. According to the evaluation criteria found in the literature of section 3.2, infrastructure is considered to be influential to the adoption process of alternative fuels. However, one can conclude that this is highly dependent on geographical location and numerous other route characteristics. Therefore, to enhance the applicability of the results the distinction between route dependent characteristics and non-route dependent characteristics are vital in the feasibility assessment. As a result, these route dependent characteristics are emphasized in the conceptual model.

3.4 JIT/JIS supply chain strategy

The previous section emphasizes the importance of the route evaluations. However, these routes should originate from somewhere. Within the automotive industry JIT/JIS is a commonly used term. As the objective is to make the automotive industry, using a JIT/JIS strategy, more sustainable, these routes should be extracted from the industry using such strategy. Furthermore, this type of supply chain is expected to be highly influential in the feasibility assessment. This will not only be expressed in the type of evaluation criteria that are applicable, but the importance of these evaluation criteria as well. To provide an insight in what a JIT/JIS supply chain is and how it works, is described below. In other words, in this section sub-research question 4 will be answered. Here an insight is given in a JIT/JIS supply chain and the actors within.

RQ 4: What is JIT/JIS and who is Involved?

3.4.1 JIT/JIS supply chain: the theory

Supply strategies are an important aspect of logistic strategies. The most important tasks of logistic strategies involve the following: increase of capacity utilisation of manufacturing and logistic resources, reduction of throughput time, reduction of in-process inventory without increasing supply risk, reduction of operation costs of manufacturing and logistic processes, increase of flexibility to answer customer’s demands, enhanced transparency of processes to support the efficiency of lean tools, integration of manufacturing processes into the whole enterprise process through ERP (Bányai & Bányai, 2017). Supply chain engineers should strive to improve the cost structure of manufacturing related logistic processes, reduce transportation, warehousing and material handling costs. Probably one the most popular tool of lean and operation management is a so called Just-In-Time (JIT) supply strategy or a Just-in-Sequence (JIS) supply strategy. This JIS supply strategy is based on a JIT philosophy, except that the goal is not only to fulfil the 7R rule (*Right* product, in the *Right* quantity, in the *Right* condition, at the *Right* place, at the *Right* time, to the *Right* customer, at the *Right* price), but also to ensure the requested sequence of products (Bányai & Bányai, 2017).

JIT is a supply strategy with the objective to eliminate waste and to improve the flow of materials. Waste elimination by reducing warehousing costs is the main driver behind this strategy (Waters-Fuller, 1995). When a JIT purchasing strategy is implemented, the production of the finished products largely depends on the on-time delivery of the components, since buffer inventories are typically reduced to a minimum. While both producer and supplier focus on eliminating inefficiencies, shortage situations are usually costlier for the producer than for the supplier (Zimmer, 2001). However, often responsibility is contractually determined to be at the logistics providers end. Today the JIT based material supply strategies of manufacturing processes are gaining more and more importance as, being flexible and reliable, they significantly increase the cost efficiency (Bányai & Bányai, 2017).

In manufacturing environments where products are build-to-order including a wide range of customization, a traditional JIT supply strategy which delivers singular variant racks to the assembly line, quickly reaches its limits. This is due to increasing warehouse space, higher implied stock levels, increased handling costs and a higher chance of confusion at the assembly line. These facts cause the need for an improved supply strategy such as JIS. In order to facilitate the production of mass customised end products in a cost-efficient way while keeping inventories low, maintaining fast throughputs and reducing the amount of working capital fixed in the process, a JIS strategy might be a viable solution (Wagner, 2011). The JIS strategy is in literature often limited to an in-house supply strategy. However, there are examples where companies go further. At VDL Nedcar a ship-to-sequence strategy is implemented. This strategy is part of a JIS strategy and is described in the literature as a strategy where the required products are sequenced outside of the manufacturing plant. The required products are sequenced either in the plant of JIS supplier or in the intermediate storage or cross docking facility. In this case, the inventories of the manufacturer are decreased and shifted back to the intermediate storage of JIS supplier or logistics service provider (Bányai & Bányai, 2017).

Parts are only delivered at the plant a couple of hours before they need to be at the assembly line. Therefore, these strategies are highly time sensitive as delayed arrivals can cause a line stop, which results in production losses and costs.

A JIT/JIS strategy goes often hand-in-hand with a Warehouse-On-Wheels (WOW) system. A WOW system involves a warehousing strategy where parts are kept in storage in semi-trailers. Therefore, reducing the amount of warehouse facilities. These semi-trailers are kept on yards near the plant and are driven to the unloading-docks when needed (Fliedner et al., 2015). Which also implies a JIT/JIS strategy. For this reason, in an automotive supply chain there are almost no rigid trucks used for transport.

3.4.2 JIT/JIS supply chain: Actors

This section is based on an internal desk research at VDL Nedcar where the problem statement, as described by them, is analysed. This provides an insight how actors within the JIT/JIS supply chain relate and interact with each other.

Plants using JIT/JIS

In the automotive industry JIT/JIS supply chain strategies are commonly used due to otherwise requirement of large warehouses, VDL Nedcar is such company. In total, there are 296 plants in Europe where passenger cars, light commercial vehicles, heavy-duty vehicles and buses are manufactured (ACEA, 2020). Some examples are: Volkswagen Auto Group , Volvo, Mercedes-Benz and PSA Group. As explained before, some of these companies are seeking to make their environmental impact less disastrous by implementing alternative fuels for their transportations activities for parts supply.

Logistic service providers

Logistic Service Providers (LSPs) are companies that facilitate the transport, in this case in Full-Truck-Loads (FTL), between suppliers and the manufacturing plants. This highly competitive market is characterized by low margins and is often known for obscure actions by exploiting foreign employees to make it profitable. LSPs driving in the automotive industry are required to have a large fleet of tractor-trailer combinations due to high transport volumes (Feld, personal communication, 2021). Often LSPs enter into partnerships or acquire sub-contractors to fulfil the large and fluctuating demand of the industry. Furthermore, due to the highly volumetric loads, transportation implies the use of so called “low-deck tractors” and “mega trailers”. These configurations involve lower coupling disk (fifth wheel) heights and smaller tires and wheels to maximize trailer inner height up to 3 meters (Feld, personal communication, 2021).

Truck manufacturers

The amount of truck manufactures is limited, especially when it comes to the production of alternative fuel powered heavy-duty tractors. Although the limited amount, there are some that are well known, take the Tesla Semi or Nikola for example. Due to their disruptive innovations, they are covered in a wide range of news articles. However, there are more mature companies who are known for their diesel application, who now are transforming towards alternative fuels as well. Volvo Trucks, Scania and DAF are some examples.

Governments

Due to the internationality of this transport modality, there are a wide range of governments involved with the transformation towards the adoption of alternative fuels in heavy-duty transport. National policy-makers are highly influential in this case. However, these policy-makers are often steered by regulations obliged by the European Union.

Interrelation between actors

As can be concluded from previous sections, there is a certain chain of influence. As made clear in their problem statement, plants such as VDL Nedcar are able to enforce this transformation when tendering for new Logistic Service Providers (LSPs) (Feld, personal communication, 2021). They are able to do this, by demanding certain percentages of the truck fleet to be driven on alternative fuels and make this contractually enforceable. Further down the chain the LSP, especially their purchasing department, are in direct contact with truck manufactures. Here, LSPs are sandwiched between different actors. On one hand, they are the customers of truck manufacturers so they can steer demand. On the other hand, they are dependent on supply. A weakness of LSPs in this chain of influence is the amount actors within a category (Feld, personal communication, 2021). The transport sector is highly competitive due to a large set of transport companies. This makes individual strength of a single LSP fairly low. Furthermore, the amount of truck manufactures, especially in the alternative fuel market, are low. Therefore, increasing the individual power of suppliers. Although it is a different application than intended to, this strongly relates to Porter's Five Forces model.

Furthermore, governments try to stimulate these type of transitions by implementing financial incentives. This can be done using two different approaches: (i) making more polluting ways of doing business less attractive and (ii) by making more sustainable ways more financially attractive. Examples of these type of incentives are: CO_2 tax and financial grants respectively (Ministerie van Economische Zaken en Klimaat, 2020), which influence the decision-making of all other actors.

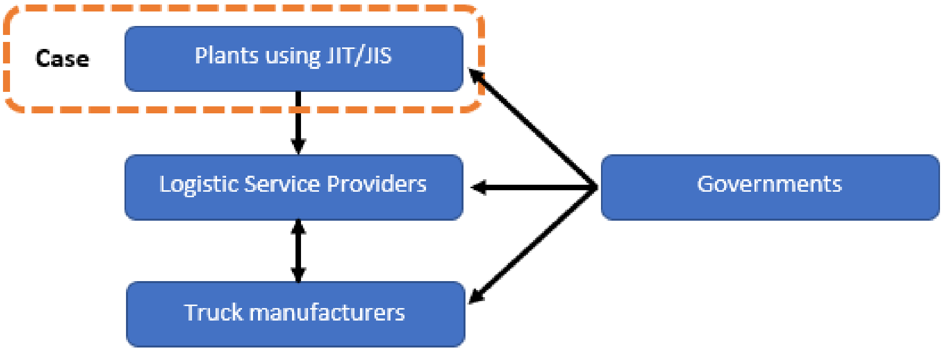

Figure 8: Chain of influence

3.5 Conceptual model: overview

At this point, all background information of all aspects related to this subject is complete. In the figure below, the visualization of the conceptual model can be consulted. Here, can be seen how the automotive industry can rank the feasibility of alternative fuels tailored to their specific needs. It should be noted that this model determines feasibility within a corporate perspective from a point of view of automotive plants that implemented a JIT/JIS supply chain strategy. In other words, the model describes the way companies could or should think when implementing alternative fuels.

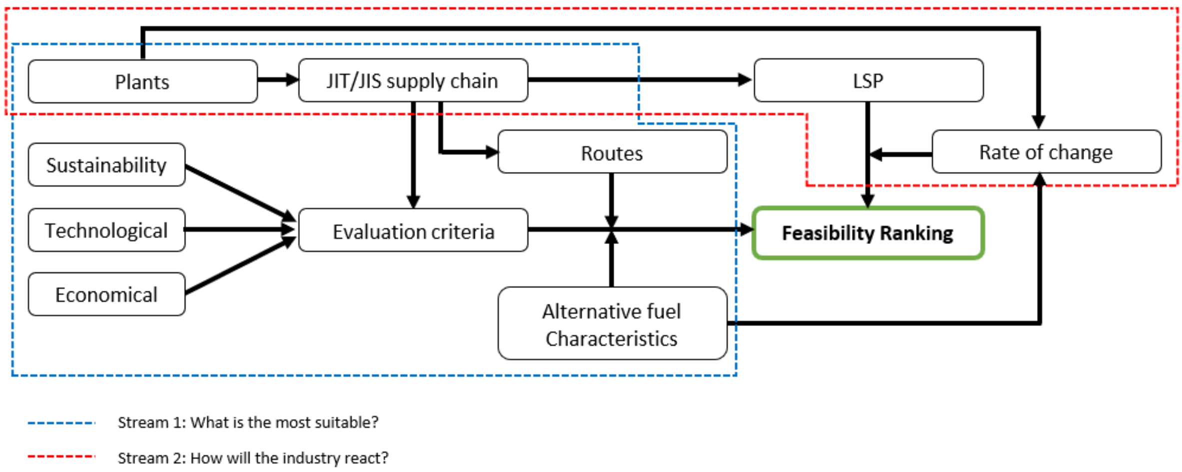

Figure 9: Conceptual model for the feasibility ranking of alternative fuels in a JIT/JIS supply chain

In figure 9, two streams are defined. This is because the feasibility ranking is influenced by two different aspects: (i) what is the most suitable alternative fuel? (ii) How will the industry react?

The first stream will define the solution that fits best within a given situation. Here, the automotive plants will define the JIT/JIS supply chain. Next, within JIT/JIS and the three perspectives, the evaluation criteria are extracted. Specifying these criteria to the routes that are used in JIT/JIS and adding the alternative fuel characteristics, will determine the best theoretical solution. By doing so, the implications of these type of supply chains should become clear. As discussed in the literature, alternative fuel characteristics, and therefore feasibility, is highly dependent on the route that is driven. Therefore, the routes within this type of supply chain are emphasized.

The second stream explains how the industry, especially logistic service providers, will react from their practical point of view. From the section that describes the actors within JIS/JIS, it became clear that the plants/factories have a certain amount influence on the rate of adoption of alternative fuels by logistic service providers. This influence is fed by the desire of the industry for a more sustainable business, regardless of the underlying incentive and can be enforced by contractually agreements when tendering for new LSPs. However, plants cannot expect to implement a 100% transformation the next day. Therefore, the view of LSPs on this transformation is influential to the feasibility of an alternative fuel to some extent. In other words, the rate of adoption of alternative fuels can be obstructed by individual LSPs due to additional burdens that often imply additional risks for the LSP. Nevertheless, the individual bargaining power of LSPs is limited due to a highly competitive market.

4 Evaluation criteria selection

First, stream 1 will be completed (see figure 10). The first step in this process is determining the evaluation criteria. As mentioned earlier, the evaluation criteria are divided into three perspectives namely: Sustainability, Technological and Economical. Within these perspectives, the criteria are based on findings from the literature and selected by doing interviews with experts and decision-makers within VDL Nedcar.

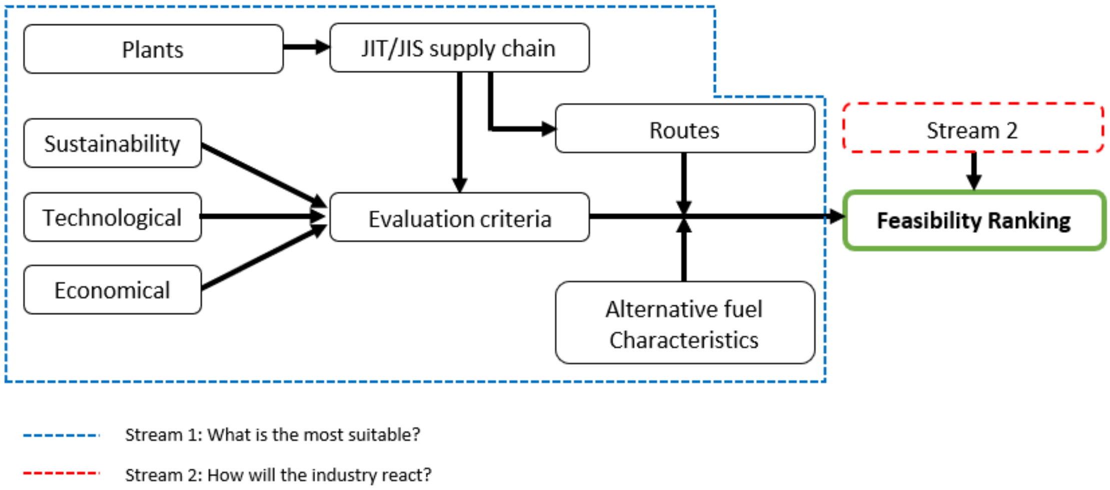

Figure 10: Conceptual model stream 1

When determining the evaluation criteria, the following strategy has been applied: First, literature was found related to alternative fuels in vehicles in general. The literature often involved a multi-criteria decision-making method, but was not limited to. Second, semi-structured interviews have been performed with decision-makers within VDL Nedcar. The interviewees have all supply chain related job descriptions and range from engineer up to general managers, see table below. During the interviews, the findings of the literature were presented to the decision-makers and they were asked their opinions. They were asked to select the evaluation criteria they find crucial to evaluate alternative fuels within their application and supply chain strategy. Furthermore, they were free to add criteria or comment on the literature.

Table 5: Interviewees to determine the evaluation criteria

Name	Function within VDL Nedcar
T. Feld	Supply Chain Engineer
R. Lindelauf	General Manager Supply Control
F. Henckens	General Manager Supply Chain Engineering

It should be noted that the evaluation criteria found in the literature sometimes are strongly related or influence each other. Nevertheless, all criteria found are listed in the tables below. Furthermore, criteria that are selected to evaluate the alternatives will be explained thoroughly to get an understanding about their meaning.

4.1 Sustainability perspective

Table 6: Sustainability related evaluation criteria

Criteria	T. Feld, 2021	R. Lindelauf, 2021	F. Henckens, 2021
Greenhouse gas emissions			
Social welfare impact			
Noise emission		x	x
Ecological impact of truck manufacturing and recycling			
Well-to-Tank emissions			
Tank-to-Wheel emissions	x	x	x
Well-to-Wheel emissions			
Life-cycle emissions			

Tank-To-Wheel emission

The term Tank-to-Wheel (TTW) refers to a subrange in a emission chain of a vehicle that extends from the point at which energy is absorbed, such as refuelling or recharging, up to the point of discharge, in other words: driving. To conclude, TTW describes the use of fuel in a vehicle and emissions when driven (CO2 emissiefactoren, 2021). In other words, TTW emission is a more specific part of the general green-house emissions.

From the interviews it became clear that, from a corporate perspective, companies are seeking to make their activities more sustainable, rather than focusing on a broader view. Therefore, all interviewees stated that only Tank-To-Wheel emission is a relevant criteria regarding green-house gas emissions, neglecting Well-To-Tank or life-cycle emissions for example. However, one interviewee stated that Well-To-Tank is important for him personally as well, but explained that from a corporate perspective it is not relevant.

Due to a strong volatile market and therefore large fluctuating production numbers in the automotive industry, emissions will be expressed in an emission per kilometre. By doing so, relevance of the results will be expanded over a large timeframe. Moreover, in the case of VDL Nedcar, due to the change by 2023 to new client(s), supplier routes might change accordingly. Expressing emissions per kilometre should provide VDL Nedcar and other plants with data to calculate emissions according to their situation without losing generalizability across the industry.

Noise emissions

This criteria refers to the noise produced during the operation of the vehicle. Especially in the first and last stage of the transportation route, this becomes an important factor. With suppliers and manufacturing plants located near residential areas, civilians find disturbance, in the form of noise, when heavy-duty diesel trucks drive near their homes. In VDL Nedcar's case, this even becomes a more crucial criteria as there are large expansions plans, what might lead to more transport activities. More important, these expansions would involve trailer yards closer to a residential area. What might lead to violation of the permits. This should be avoided and potentially can be by implementing an alternative fuel.

4.2 Technological perspective

Table 7: Technological related evaluation criteria

Criteria	T. Feld, 2021	R. Lindelauf, 2021	F. Henckens, 2021
Reliability		x	
Performance (weight, load length)	x	x	x
Refuelling infrastructure	x	x	x
Refuelling time	x	x	x
Safety		x	
Driving range	x	x	x
Perceived quality/comfort			
Transport time	x	x	x
Energy availability	x	x	x
Manufacturers' warranties			
Service quality of manufacturer			
Downtime		x	
Power density/ fuel efficiency			

During the interviews it became clear that the experts highly value safety aspects of these trucks. However, they assumed this criteria to be a boundary condition for adoption. Therefore, safety is not considered as an evaluation criteria.

Truck Performance

Performance can be explained in numerous ways. From the interviews, it became clear that there are three sub-criteria when assessing an alternative fuel performance wise:

1. Load length
2. Load weight
3. Truck power

As explained earlier, a JIT/JIS supply chain strategy goes often hand-in-hand with a Warehouse-On-Wheels strategy. This implies the use of tractor and semi-trailer combinations. The maximum dimensions and weight of these combinations are set by European legislation (Evofenedex, 2021). To ensure maximum efficiency, modern trucks are built in such way that load lengths are maximised and are kept as light as possible. By implementing alternative fuels this efficiency might be at risk. This is due to potential heavier or larger fuel tanks and engine components. Besides that, it is important that alternative fuel powered trucks can cope with modern-day road situations. For example, these trucks should accelerate similar to diesel trucks in order to ensure drivability. Therefore, power outputs will be evaluated as well.

Refuelling infrastructure

The interviewees listed refuelling infrastructure as an evaluation criteria applicable for their decision-making. Refuelling infrastructure involves the refuelling convenience, in the sense of the amount of refuelling stations available.

The decision-makers made it clear that within this criteria feasibility of certain routes is a boundary condition and potential additional transport time due to detours, should be evaluated. They stretched that, if an alternative fuel is possible from certain suppliers to the plant, additional transport time should be kept to a minimum. In other words, detours to reach refuelling stations, to make a route feasible, should be considered but within reason. From the literature, it became clear that this criteria is dependent, amongst others, geographical location and route characteristics.

Refuelling time

Refuelling time describes the time it takes to fully refuel or, in the case of battery electric vehicles, recharge a truck. This is connected to the total transport time as well. When refuelling time increases, this can have a significant impact on total transport time. Especially when considering battery electric vehicles, this could be influential. Although, convenient opportunities for refuelling occur due to frequent obligated breaks, refuelling time should be kept to minimum.

Driving range

The driving range explains the amount of kilometres a truck can drive on one tank or charge. In other words, the maximum distance a truck can drive without refuelling. This, in combination with refuelling time and refuelling infrastructure, can have noticeable impact on total transport time.

Transport time

The interviews made it clear that the transport time is crucial in a JIT/JIS supply chain. This is due to a short “pearl chain” horizon. A pearl chain refers to the amount of fixed or configurated production slots. VDL Nedcar uses a pearl chain horizon of eight days (Feld, personal communication, 2021). In other words, VDL Nedcar knows eight production days before actual production what car is going to be build and in what configuration. This means the whole process of ordering parts to the point of assembly, including transport from all over Europe, is allowed to take a maximum of eight days. In this example, safety stock is neglected. Moreover, it is important to note that, JIT/JIS parts are only transported using Full-Truck-Loads (FTL). When the pearl chain horizon is non-variable and daily productions numbers decrease, it would take more time before a FTL is full. Adding this to a potentially increased transport time, this could have severe impact on efficiency. This strengthens the importance of transport time.

Energy availability

This evaluation criteria refers to availability of a fuel. In other words, can the current and future supply of the fuel cope with (expected) demands. A large scale electric driven heavy-duty fleet, could increase electricity demand significantly. Is the future electric power grid and energy generation able to meet this demand? For other fuels, the same applies: Are production numbers sufficient to refuel a heavy-duty fleet?

4.3 Economical perspective

Table 8: Economical related evaluation criteria

Criteria	T. Feld, 2021	R. Lindelauf, 2021	F. Henckens, 2021
Purchase costs	x	x	
Operational costs	x	x	x
CO2 Tax	x	x	x
Financial grants/incentives	x	x	x
Current fuel costs	x	x	x
Future trend fuel costs	x		x
Service and maintenance costs	x	x	x
Taxes and insurance	x	x	
Depreciation/ resale value	x	x	
Conversion/ implementation costs		x	
Fuel price stability		x	x

Purchase costs and depreciation

Purchase costs refers to the CAPEX. However, as became clear from the interviews, every cost item relates to an average cost per kilometre assuming a yearly mileage. This will be calculated as followed:

$$\frac{CAPEX - Depreciation}{Life\ expectancy\ (km)}$$

The interviewees explained that this criteria on its own, is not a selection criteria. It is only usable when combined with all other costs related criteria, converted to costs per kilometre. This cost per kilometre comes from the fact that LSPs bill their customers in a price per kilometre and is therefore considered an industry standard business model. However, it could be argued that due to longer recharging times of battery electric vehicles, this business model could shift towards a model where a price per time unit is billed.

Tax and incentives

Due to European climate agreements, countries are looking for ways to push companies to transform to a more sustainable way of doing business. In the transport sector, there are a couple of incentives to make it more economically attractive for companies. On the other hand, there are plans to implement a so called CO_2 tax. This tax should make the current way of doing business less attractive due to increased costs. From the interviews, it became that this criteria should be incorporated in the costs per kilometre equation as well.

Current and future fuel costs

Current fuel costs involves the current price of the fuel, either in kilograms or litre. Current fuel costs values are more certain and are easy to incorporate in the cost per kilometre calculation. However, future fuel costs are based on predictions and are therefore highly uncertain. Nevertheless, the interviewees emphasized that fuel cost is often the largest contributor to the operational costs.

Maintenance costs

As many of the fuels are still in the development phase, maintenance cost findings are often based on predictions. Regardless of the additional uncertainty, the decision-makers explained the importance of this criteria, as this potentially can have a significant impact on the cost per kilometre equation as well.

Fuel price stability

Fuel price stability refers to short-term expected price fluctuations. Diesel, for example, fluctuates in price from day to day. This price fluctuates fairly consistent but is highly dependent on foreign countries. The decision-makers aim for better price stability without large fluctuations. This is due to the small profit margins made in the industry as described. Here, transport is one of the largest cost item. This value is highly uncertain due to the early stage of development of some alternative fuels and therefore could add a significant amount of risk to operations. Fuel price stability is the only criteria that will not be incorporated in the cost per kilometre equation and is therefore a criteria on its own.

4.4 Selected evaluation criteria

In this chapter the following sub-research question is answered:

RQ 5: What are conceptually important feasibility criteria for alternative fuels when a JIT/JIS supply chain is applied?

Based on the findings in the section above, the selected evaluation criteria are structured in such way that it represents the case. It should be mentioned that the individual criteria are not new but the structure in which they work is. Therefore, it is expected that this new structure has a tremendous effect on the weights of these criteria.

When referring back to the literature, one can see significant differences. In this structure, criteria on its own are not relevant but the relation between different criteria is emphasized, such as in the economical perspective. Furthermore, in the literature can been seen that, for example, refuelling infrastructure is a criteria on itself. In this structure, it is related to refuelling time and driving range equating to a total transport time. Furthermore, where literature incorporates Well-To-Wheel or lifecycle analysis, here, only a Tank-To-Wheel is considered as relevant by decision-makers. Moreover, in the this structure “noise emission” is evaluated as well, which only occurs four times in the literature. Contradicting to the literature were transport time is only mentioned briefly twice, in this model it is labelled as a main criteria. To conclude, at first glance this model might be similar to existing literature. However, one can see significant differences in the structure of the evaluation criteria models used in the literature and the one build here for applying it to a corporate environment.

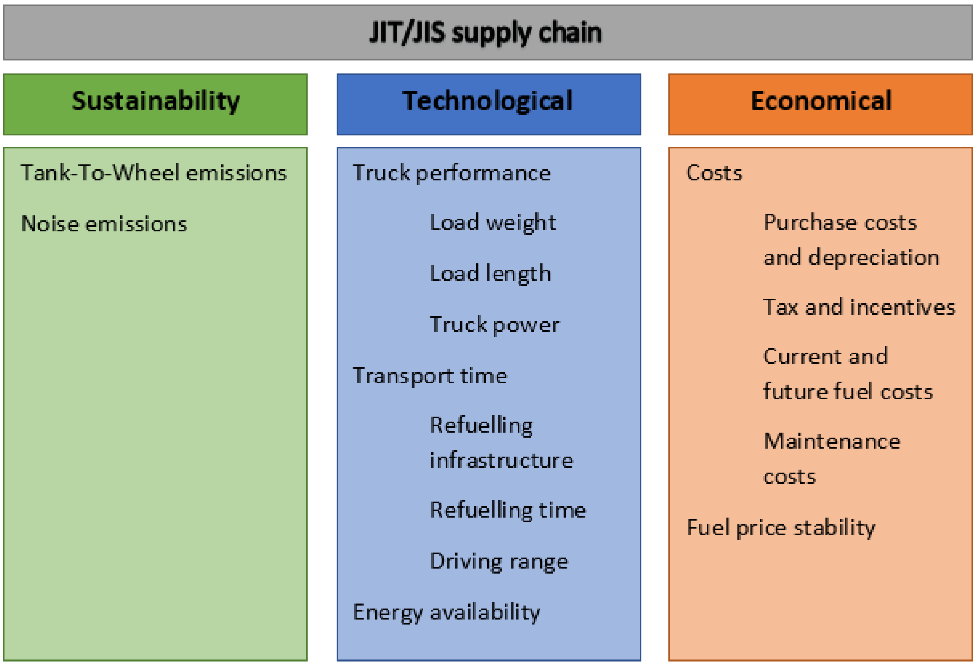

Figure 11: Selected evaluation criteria structure

In the figure above, the restructured evaluation criteria model is explained. This model is based on seven criteria that will be weighted using the Best-Worst method in the next chapter. Some of these criteria are divided into sub criteria which equate to the sum of the main criteria. However, it is emphasised that the sub criteria are not weighted. The sub criteria are used to determine the score of the main criteria. This can be explained by the interviews in which is stated that some of these criteria are not relevant on its own but relate to an overall criteria.

5 Criteria weights

The next step in the process is determining the weights of these evaluation criteria. Here, the Best-Worst method is used. For determining these weights, five interviews have been performed. By taking the average of all the individual findings, one can find a well underpinned weights with regard to the evaluation criteria.

5.1 Best-Worst method

Findings interview T. Feld

Feld (2021) stated during the interview that: due to the fact that transport costs are directly billed to the customer, which is BMW Group in this case, one would say that this criteria is not important. However, to stay competitive in the market, especially when looking for new customers, cost per kilometre is considered to be the most important evaluation criteria. He further states that transport time is, as expected, an important criteria within a JIT/JIS strategy. However, due to declining production numbers and low interest, there are more possibilities for cheaper stock and a larger surface available for warehousing. This creates possibilities for larger amounts of safety stock. Therefore, making transport time less critical in the current situation. However, this study involves a larger timeframe with notable chances of higher production numbers in the future. In addition, he explained additional transport time could be calculated in when assuming a worst case scenario. Furthermore, he emphasized the importance of energy availability. He explained that this criteria involves a lot of risk, as it could lead to line stops when fuels are not available. Truck performance, especially load length, is related to a total cost per car (product) which is directly related to the competitive position as well, he states. This can be explained by stating the relation between additional costs per product and smaller load length: When load lengths of a Full-Truck-load decrease, more trips per product are needed what in turn leads to higher costs. Furthermore, noise emissions is weighted fairly low. This is due to the fact that when an alternative fuel powered truck is beneficial to noise emission, it is considered a "nice addition". However, if an alternative fuel is not beneficial to this problem, it can be tackled by implementing other measures, such as sound barriers or a "kiss and ride". At last, Feld noted that: "Although the underlying goal of this study is to make our transportation activities more sustainable, Tank-To-Wheel emissions is not the most important evaluation criteria, even though it actually should be given the current climate change" (Feld, 2021).

Findings interview F. Henckens

Henckens (2021) explains that it is the objective to reduce CO_2 emissions with 25% by 2025 as part of their corporate strategy. However, the costs are the most decisive criteria when adopting new innovations. Especially when considering a corporate environment. Therefore, Tank-To-Wheel emission and costs are close to each other on the rank of importance. Truck performance and transport time are weighted almost equal. Henckens (2021) states: 'This due to the fact that the same amount parts need to be delivered on time and on the right place without any compromises". In the case of VDL Nedcar, this translates to their competitive position in the market, as the objective is to keep their costs per car (product) as low as possible. Furthermore, he explains that he sees energy availability as an important criteria at first, but explains that when an alternative fuel is adopted, it becomes less important. This is due to the fact that, eventually supply will meet demand unless an energy source is exhaustible in the short term (Henckens, 2021). He explains that after the importance of energy availability weakens, the importance of fuel price stability rises. He states that this criteria could have a higher impact on the operational phase over a longer time window. However, this is considered to be less important with regard to the transformation on its own. At last, he describes the importance of the noise emissions. He states that they are obligated to reduce these as well and if an alternative fuel could contribute towards accomplishing this goal, it would benefit the company in general.

Findings interview R. Lindelauf

Lindelauf (2021) emphasized the importance of costs. He explained that without costs competitiveness a plant in the automotive industry has no right of existence. An exemption would be a plant focusing on a niche. Therefore he stated that all other evaluation criteria are subordinated to costs. In other words, if an increase in costs would cause a significant loss in market competitiveness an alternative fuel is considered infeasible from the start. Energy availability is considered to be the least important. He explained that by confirming the supply and demand statements that are made by other interviewees as well. When discussing the other criteria he explained that if costs are competitive the others will provide “a little extra”. He therefore explained the relatively low ranked sustainability related evaluation criteria even though these were the incentive to start this research. When discussing sustainability related transformations in general, he explained the required balance of sustainable innovations and potential up costs. At last, potential noise reductions are weighted relatively low. He mentioned that noise is only associated with VDL Nedcar when it is near the plant. However, noise disturbance can be solved by other measures as well. In other words, noise reductions on highways has little influence on the decision-making.

Findings interview H. van Mierlo

As team leader of the transport control department, van Mierlo (2021) explained his view on the transition towards alternative fuels. He explained that his department has the highest interest in transport times. According to him, the process is highly optimized and is highly sensitive to increased times or delays. For example, LSPs are obligated to make announcements when arrival time is delayed with two hours or longer. Furthermore, he explained that on a 580 kilometre trip LSPs are allowed to take 8-9 hours for driving and an additional 2-3 hours for loading activities, for example. In other words, large and frequent delays are out of question. This is due, optimization of the trailer-yard, unloading capacity and other material handling activities. Therefore he also made the connection with the truck performance. He explained that, if trailers are able to load more volume of mass, there are less trailers required, both on the road and on the yard. Moreover, internal actions and handling activities should not increase by implementing alternative fuels, as he describes. Energy availability is described by van Mierlo as a criteria that is a LSPs’ responsibility, but he acknowledges potential influences on the supply chain. He explained from the view of the transport control department, costs are not as important as to other departments, as long as it stays within budget, he emphasized. With regard to noise emission he explained that, when transport times are less and highly reliable, the department is able to schedule transport in such ways that peaks in noise disturbance can be flattened out. Therefore, noise emission is perceived as one with low importance. At last, he explained that when can be advertised with a sustainable alternative fuel, to which extend is less important. Therefore, Tank-To-Wheel emissions is considered to be less important in the evaluation process between alternative fuels. He summarized his statements by explaining the way his department perceives this transformation. “First, the operational aspects should be up to standard. Second, costs need to be within budget and third, when the others aspects are approved, the societal impact is considered additional benefit" (van Mierlo, 2021). As nuance, he explained that he solely looks at this transition from an operational view from the transport control department.

Findings interview L. Heiligers

Just as BMW Group does, VDL Nedcar uses sustainability as a marketing or PR tool. That was the initiator for this research according to Heiligers (2021). However, he explains that with regard to a corporate perspective, costs are considered to be the most important criteria as that determines a company's right for existence. Heiligers explains that noise emissions are the least important criteria. This due to the fact, that there are several other (easy) solutions to reduce local noise emissions. Kiss and rides strategies, sound barriers or forestation are some examples of that. Heiligers acknowledge the different classification of truck performance and costs per kilometre with regard to the perspectives. However, he explains that those are both related to an overall financial item. Namely, the costs per product. Therefore, he emphasized the importance of the truck performance. Furthermore, he explained the importance of fuel price stability. He took the current shipping container as an example. Here, he elaborates the large increase in shipping costs caused by a shortage in containers, which should be avoided or accounted for. Energy availability, is weighted relatively low by Heiligers (2021). He explains that by describing market forces: "Supply will meet demand. When large scale implementation occurs, production numbers of the fuel will increase". Moreover, from his statements, regarding this criteria, can be concluded that VDL Nedcar aims to be an early adopter rather than to be a part of the late majority. When assessing transport time, he explains the importance of the criteria with regard to JIT/JIS process and the pearl chain within, but he also emphasized the relation of this criteria to potential additional costs and financial risks. This is due to potential additional FTE's and transport costs caused by refuelling times and detours respectively.

5.1.1 Weights overview

In this section the following research question is answered:

RQ 6: What are the weights of the evaluation criteria within the case study?

Table 9: BWM weights overview

	Sustainability		Technological			Economical		
	Tank-To-Wheel emissions	Noise emissions	Truck performance	Transport time	Energy availability	Costs	Fuel price stability	Ksi
T. Feld	0,0926	0,0390	0,1852	0,1235	0,1852	0,3217	0,0529	0,0487
F. Henckens	0,2597	0,0779	0,1558	0,1558	0,0390	0,2857	0,0260	0,0519
R. Lindelauf	0,0996	0,0830	0,1245	0,1659	0,0325	0,3950	0,0996	0,1028
H. van Mierlo	0,0343	0,0654	0,2289	0,3662	0,1144	0,1144	0,0763	0,0916
L. Heiligers	0,0882	0,0294	0,1471	0,1471	0,0882	0,3529	0,1471	0,0882
Average	0,1149	0,0589	0,1683	0,1917	0,0919	0,2940	0,0804	0,0767

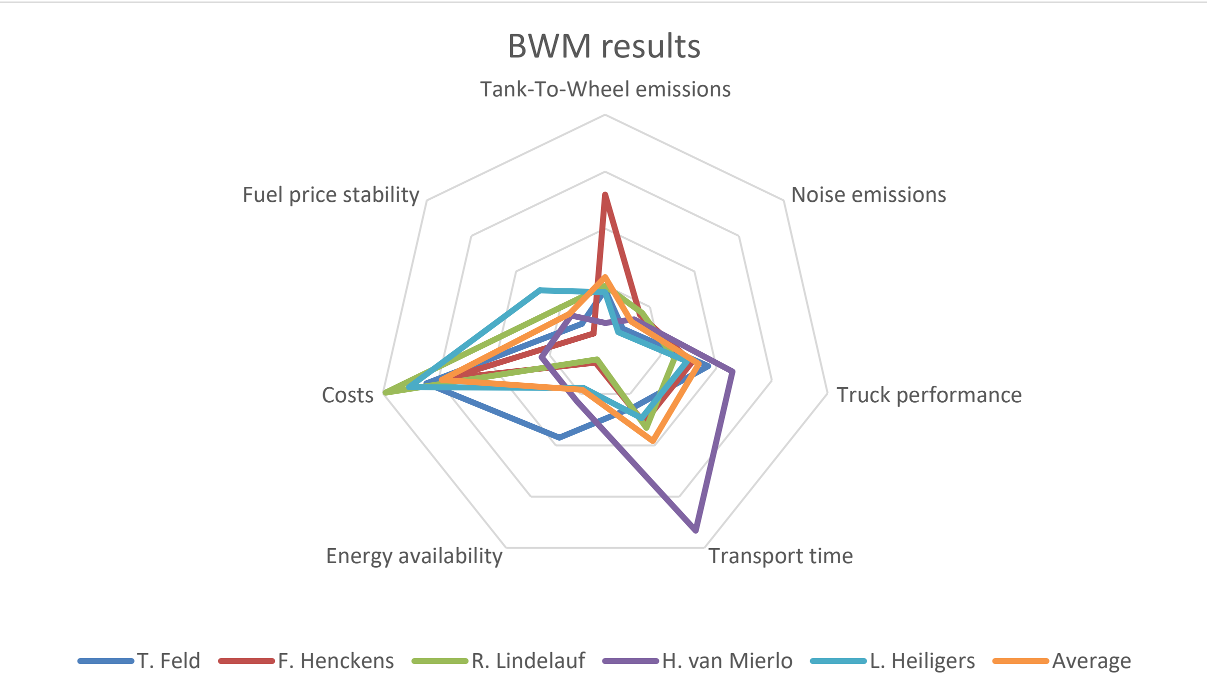

Figure 12: BWM weights distribution

From the figures can be concluded that costs are highly influential in this decision-making process. Numerous interviewees explained that by stating the corporate view on the transformation towards sustainability. As expected, within the JIT/JIS supply chain, transport time is considered to be highly important. Although, to what extend this importance is, is depending on who you ask. Furthermore, truck performance is heavily weighted. As many interviewees explained, this is due to potential higher costs and ease of operations. Except from one interviewee, Tank-To-Wheel emissions is weighted remarkably low, despite its function as research initiator.

5.2 Implication of the JIT/JIS supply chain strategy

Due to the restructured evaluation criteria model, it is difficult to compare the individual weights of the criteria to other research in the field of alternative fuel powered heavy-duty trucks. However, the global weights of the perspectives are able to provide an insight in the implications of the JIT/JIS supply chain. When comparing these results to a research done by Yavuz et al. in 2015, one can see a higher weights of sustainability related criteria. Yavuz (2015) stated a global weight of the sustainability perspective of 0,3 out of 1. In this research, sustainability is weighted at around 0,17 out of 1. On the other hand, Yavuz (2015) states lower weights of both economical as well as technological criteria, with a difference compared to this research of 17% and 14% respectively. In other words, within the JIT/JIS supply chain the technological and economical aspects of alternative fuels are ought to be more important for this transformation than in other applications. This confirms the large weighting differences as predicated in previous chapter.

6 Alternative fuel scores

In previous chapters, the evaluation criteria and their weights are established. The next step in the process is determining the scores of each alternative fuel with regard to this specific application. Therefore, routes from the case are extracted that will be used to determine these scores. In other words, this chapter describes the intersection of evaluation criteria, alternative fuel characteristics and routes of the conceptual model. This is marked with the red dot in figure 13.

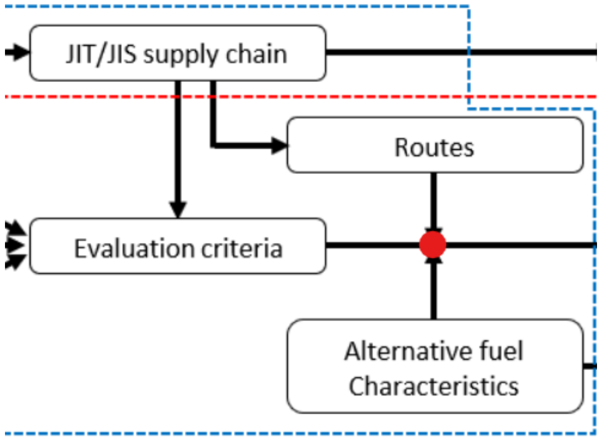

Figure 13: Conceptual model stream 1 focus point

6.1 Initial findings

The following table is used as a baseline to determine the scores of the alternative fuels. Here, all 2023 expectations with regard to the evaluation criteria are explained and 2030 expectations are stated as far as the literature could suffice. For more explanation one can consult appendix A.

These findings are based on a literature study that started with consulting scientific literature. Unfortunately, scientific papers couldn't fill all knowledge gaps. Therefore, grey literature has been consulted as well. This mainly consisted out of company publications of numerous truck manufacturers and fuel distributers as well as governmental documents. Still, not all knowledge gaps were filled. Therefore, master theses from previous TU Delft were processed. After this, the fuel price stability of HVO was still unknown. After contacting refuelling stations, no answers could be provided. Therefore, this value is an assumption. Furthermore, due to a lack of literature and high uncertainty, 2030 values are incomplete. However, the values that are provided, could give an insight in future developments.

Table 10: Initial findings to determine scores

			2023		2030		
	Weighted criteria	Sub-criteria	Findings	Based on (source)	Findings	Based on (source)	Remarks
FCEV	Tank-To-Wheel emissions		100% reduction	(Crabtree & Dresselhaus, 2008)	100% reduction	(Crabtree & Dresselhaus, 2008)	
	Noise emissions		100% reduction	(Crabtree & Dresselhaus, 2008)	100% reduction	(Crabtree & Dresselhaus, 2008)	
	Truck performance						
		Load length	No effect	(Oostdam, 2019)	No effect	(Oostdam, 2019)	
		Load weight	No effect	(Oostdam, 2019)	No effect	(Oostdam, 2019)	
		Truck power	No effect	(Oostdam, 2019)	No effect	(Oostdam, 2019)	
	Transport time						
		Refuelling infrastructure		(H2.live, 2021)			Route dependend score
		Refuelling time	66% time increase	(Oostdam, 2019; Nikola ,2019)	<66% time increase	(Oostdam, 2019)	
		Driving range	400-600 km	(Hyzon motors, 2021)			
	Energy availability		Sufficient	(Peters et al., 2021)	Sufficient	(Peters et al., 2021)	Provided that production scales
	Costs						
		Purchase costs and depreciation	0,27 - 0,41 €/km	(Oostdam, 2019; Hyzon motors, 2021)	0,21 €/km	(Moultak et al., 2017)	
		Tax and incentives	No additional tax, Grants possible	Rijksoverheid, 2021A)	Uncertain		
		Fuel costs	0,77 €/km	(Oostdam, 2019)	0,08 €/km	(Oostdam, 2019; Weeda, 2019)	
		Maintenance costs	0,11 €/km	(Hyzon motors, 2021)			
	Fuel price stability		20% volatility	(Alterman S. , 2012)			
BEV	Tank-To-Wheel emissions		100% reduction				Route dependend score
	Noise emissions		100% reduction				
	Truck performance						
		Load length	0-1 meter reduction	(Tesla, 2021)			
		Load weight	1.350 kg reduction	(Transport and Environment, 2020)	0 kg lost	(Transport and Environment, 2020)	
		Truck power	0-30% reductions	(DAF, 2021)			
	Transport time						

		Refuelling infrastructure		(Oplaadpunten.nl, 2021)			Route depended score
		Refuelling time	>75 minutes	(DAF, 2021)			Route depended score
		Driving range	200-800 km	(DAF, 2021; Tesla, 2021)			
	Energy availability		Sufficient	(Earl et al., 2018)	Sufficient	(Faddel et al., 2018)	Provided that innovation rates increase
	Costs						
		Purchase costs and depreciation	0,16 €/km	(Cleantechnica, 2021)			
		Tax and incentives	No additional tax, Grants possible	Rijksoverheid, 2021A)			
		Fuel costs	+/- 0,28 €/km	(Earl, et al., 2018)	+/- 0,07 €/km	(Earl, et al., 2018)	
		Maintenance costs	0,10 €/km	(Earl, et al., 2018)			
	Fuel price stability		40% volatility	(Ofgem, 2021)			
HVO	Tank-To-Wheel emissions		+/- 30% reduction	(Karavalakis et al., 2016; Sugiyama et al., 2011)	-		Route dependend score
	Noise emissions		No reductions				
	Truck performance						
		Load length	No effect	(Sugiyama et al., 2011)	No effect	(Sugiyama et al., 2011)	
		Load weight	No effect	(Sugiyama et al., 2011)	No effect	(Sugiyama et al., 2011)	
		Truck power	No effect	(Sugiyama et al., 2011)	No effect	(Sugiyama et al., 2011)	
	Transport time						
		Refuelling infrastructure	Sufficient	(Peters et al., 2021)			Due to ease of conversion
		Refuelling time	No effect	(Sugiyama et al., 2011)			
		Driving range	0-6 % decrease	(Kuronen & Mikkonen, 2007)			
	Energy availability		Sufficient	(Peters et al., 2021)	Uncertain		Due to natural sources
	Costs						

		Purchase costs and depreciation	0,09 €/km	(Volvo, 2021)			Equal to diesel
		Tax and incentives					
		Fuel costs	0,36 €/km	(DCB Energy, 2021)			
		Maintenance costs	0,15 €/km	(Earl, et al., 2018)			Equal to diesel
	Fuel price stability		20% volatility	(Tamoil, personal communication 2021)			
LNG	Tank-To-Wheel emissions		15-23% reduction	(Peters, et al., 2021; Volvo, 2021)			Route dependend score
	Noise emissions		12% reduction	(Nationaal LNG Platform, 2021)			
	Truck performance						
		Load length	No effect	(Volvo, 2021)	No effect	(Volvo, 2021)	
		Load weight	No effect	(Volvo, 2021)	No effect	(Volvo, 2021)	
		Truck power	No effect	(Volvo, 2021; IVECO, 2021)	No effect	(Volvo, 2021; IVECO, 2021)	
	Transport time						
		Refuelling infrastructure	Sufficient	(Heckler et al., 2020)	Sufficient	(Heckler et al., 2020)	Route depended score
		Refuelling time	No effect				
		Driving range	95-1600 km	(Smajla et al., 2019; IVECO, 2021)			
	Energy availability		Sufficient	(Smajla et al., 2019)	Sufficient	(Smajla et al., 2019)	
	Costs						
		Purchase costs and depreciation	0,16 €/km	(Anderhofstadt and Spinler, 2019; Westport Fuel Systems, 2021)			
		Tax and incentives	0,187 €/kg fuel compensation	(Volvo, 2021)	No possibilities	(Peters et al., 2021)	Fuel compensation only confirmed untill 2021
		Fuel costs	0,18 €/km	(DCB Energy, 2021)			Incentives subtracted
		Maintenance costs	0,22 €/km	(Smajla et al., 2019)			
	Fuel price stability		20% volatility	(Alterman S. , 2012)			

6.2 Route independent scores

When assessing the alternative fuels, some criteria are dependent on the routes that are driven. In the table below, one can find which criteria are considered to be route dependent. The route independent scores are directly derived from the initial finding table in previous section.

Table 11: Route dependency

Criteria	Route dependency	Nominal score (0-10)			
		FCEV	BEV	HVO	LNG
Tank-To-Wheel emissions	Dependent	-	-	-	-
Noise emissions	Independent	10	10	0	1,2
Truck performance	Independent	10	9	10	10
Transport time	Dependent	-	-	-	-
Energy availability	Independent	7	7	6	8
Costs	Dependent	-	-	-	-
Fuel price stability	Independent	8	6	8	8

It could be argued whether or not the evaluation criteria related to cost per kilometre is route dependent. In the sense of a predefined route and a total cost, one could determine the cost per kilometre. However, when alternative fuels are implemented it could be necessary to take detours for a route to become technological feasible. This could lead to additional kilometres driven and could therefore result in a higher costs with regard to certain supply routes. Therefore, the evaluation criteria related to cost per kilometre will be multiplied with the potential additional kilometres to derive a well-argued score, making it route dependent.

Furthermore, a disclaimer need to be made. Regarding energy availability of all alternative fuels, available research is limited. In other words, the scores that are presented above are based on qualitive statement made by existing literature. Therefore, the reliability and the validity of these scores are questionable as they are based on assumptions. In other words, those scores are not determined by a scientific method but based on “reading between the lines” in existing literature. The same applies for the fuel price stability of HVO. No data was available regarding this criteria, thus an assumption has been made.

6.3 Route dependent scores

In this section, the route dependent scores will be explained. These findings are based on the following assumption: (i) the trip will involve a single driver inbound route, (ii) regular breaks will be conform legislation and (iii) current refuelling methods (hoses or charge plugs) are compatible with heavy-duty trucks. Furthermore, the scores will be based on the 2023 findings from chapter 6.1. The 2030 findings are not considered, due to highly uncertain values and incomplete data.

Before the route dependent evaluation criteria can be scored, first the representative routes need to be determined. As explained earlier, this will be done by using the case. Using their data, routes are selected which are largely diversified. This is done to ensure specific results to certain applications that can be generalized to a large span of situations.

To be able to make well-argued scores, the following key assumptions with regard fuel characteristics have been made. These assumptions are based on the literature findings as presented in table 10 .

Table 12: Key assumptions

	FCEV	BEV	HVO	LNG
TTW emissions	100% reduction	100% reduction	30% reduction	19% reduction
Refuelling time	15 min.	100 min.	10 min.	15 min.
Driving range	500 km	300 km	940 km	1100 km
Cost per kilometre	1,18 €/km	0,54 €/km	0,60 €/km	0,56 €/km

6.3.1 Route scoring method

In order to score the criteria, a calculation method has been developed. These calculations ensure a unambiguously scoring method, which ranges between 0 (lowest score) and 10 (highest score). As explained earlier, all parameters are based on the initial findings table 10, which is retrieved from the literature, or route specific findings.

Diesel is used as a baseline for the scores. In other words, when an alternative fuel benefits an evaluation criteria compared to diesel, scores goes from 0 (not beneficial) to 10 (most beneficial). When an evaluation criteria in negatively affected the score goes from 0 (most negatively impacted) to 10 (no negative impacts).

An alternative for this scoring method could be normalizing. This would show the scores related to the other alternative fuels. However, this neglects diesel. The scores should be compared to diesel to assess feasibility as that will define the impact on the industry. In other words, normalizing the results could mean a high score for a fuel in a certain situation, but which is still very low compared to diesel, making it not or less feasible than the diesel comparison results will show.

Route Tank-To-Wheel emission score:

$$Score = 10 - \frac{AF_{Rl}}{D_{Rl}}\left(1 - TTW_{\frac{r}{km}}\right) * 10$$

Route transport time score:

$$Score = 10 - \frac{\frac{AF_{Rl}}{v} + RFT * n - \frac{D_{Rl}}{v}}{\frac{D_{Rl}}{v}} * 10$$

Route cost score:

$$Score = 10 - \frac{AF_{Rl} * AF_{\frac{c}{km}} * TI - D_{Rl} * D_{\frac{c}{km}}}{D_{Rl} * D_{\frac{c}{km}}} * 10$$

With:

$$0 \leq Score \leq 10$$

Table 13: Parameter description

Parameter	Unit	Remarks
AF_{Rl}	km	Route length of alternative fuel
D_{Rl}	km	Route length of diesel
$TTW_{\frac{r}{km}}$	Reduction/km	Emission reduction per kilometre of alternative fuel
v	Km/h	Average travelling speed (80 km/h)
RFT	h	Refuelling time
n	-	Number of refuelling occurrences on a trip
$AF_{\frac{c}{km}}$	Euro/km	Costs per kilometre of alternative fuel
$D_{\frac{c}{km}}$	Euro/km	Costs per kilometre of diesel (0,52 euro/km)
TI	%	Transport time increase of route using alternative fuel

6.3.2 Route selection

In order to score the route dependent evaluation criteria, the data of the case has been analysed. This data involved specifications of JIT/JIS parts manufacturing plants. Here, location was a key parameter. There were in total 33 JIT/JIS suppliers found within the case. The distribution of these supplier can be found below. These suppliers are located within a range between 3 and 1.100 km. furthermore, a benchmark has been set that at least 2/3 of transported volume is covered by the selected routes. By selecting supplier clusters, a single route can be used to cover several suppliers. In other words, the number of routes to be evaluated can be decreased by starting in a cluster , without losing reliability of the results. These routes originate in the centre of a so called supplier cluster centre. In such cluster, at least two supplier are located within a predefined radius.

Figure 14: Overview of JIT/JIS suppliers within the case

In order to, find representative clusters, a formula has developed to act as a selection criteria.

$$\begin{matrix} S_{L_1-L_2} \\ S_{L_2-L_n} \\ \dots \\ S_{L_n-L_m} \end{matrix} \leq 0.15 * \frac{\sum_{i=1}^{m} S_{L_i-NC}}{m}$$

With: $m \geq 2$

Table 14: Symbol description

Symbol	Explanation
$S_{L_n-L_m}$	Distance between supplier $L_n$and L_m (km)
S_{L_m-NC}	Distance between supplier L_m and VDL Nedcar (km)
m	Number of suppliers

This formula assesses potential clusters. Here is stated that within a selection of suppliers the distance between suppliers is less than 15% of the average distance to VDL Nedcar with regard to the suppliers selected. In other words, how larger the travel distance, how larger the cluster is allowed to be. Furthermore, a cluster includes a minimum of two suppliers. Implementing this method, four clusters are found.

Table 15: Cluster routes

Route number	Cluster	Number of suppliers	Cluster centre	Max. distance between suppliers	Distance to VDL Nedcar
1	1	6	Southam (GB)	50 km	+/- 640
2	2	2	Regensburg (DE)	80 km	+/- 610
3	3	2	Dobrany (CZ)	30 km	+/- 715
4	4	4	Piensk (PL)	115 km	+/- 770

These supplier cluster transport in total almost 10.000 m^3 per week of parts. This equates up to 124 Full-Truck-Loads per week. This is about 50% of the total transported goods within the JIT/JIS supply chain. Assuming consistent production numbers and a 47 week work year, this would result in close to 4 million driven kilometres per year. Assuming CO_2 emissions of 0,65 kg/km of Euro 6 engines (Vermeulen, et al., 2017), this equates to 2,6 million kg of CO_2 emitted per year.

Looking at the supplier map, one can find several nearby located suppliers which do not form a cluster. However, due to the diversification, these should be evaluated as well. Therefore, within a range between 0 and 500 km, individual suppliers are selected. A boundary condition for selecting an individual supplier is a significant geographical difference with regard to the clusters.

Table 16: Individual supplier routes

Route number	Individual supplier	Location	Distance to VDL Nedcar
5	1	Morsbach (DE)	+/- 180 km
6	2	Luneburg (DE)	+/- 475 km
7	3	Prémont (FR)	+/- 250 km
8	4	Holtum (NL)	+/- 3 km

From these findings to total amount of routes to be researched sum up to eight. With the additional four, there is more diversity in the routes, both in geographical direction and in driving distances. By adding the individual routes, a more specified conclusion can be drawn and offers the chance for a more generalizable result as well. These eight routes represent 18 of the total of 33 suppliers and are currently responsible for about 71% of total transported volume within the JIS/JIS supply chain.

Figure 15: Routes overview

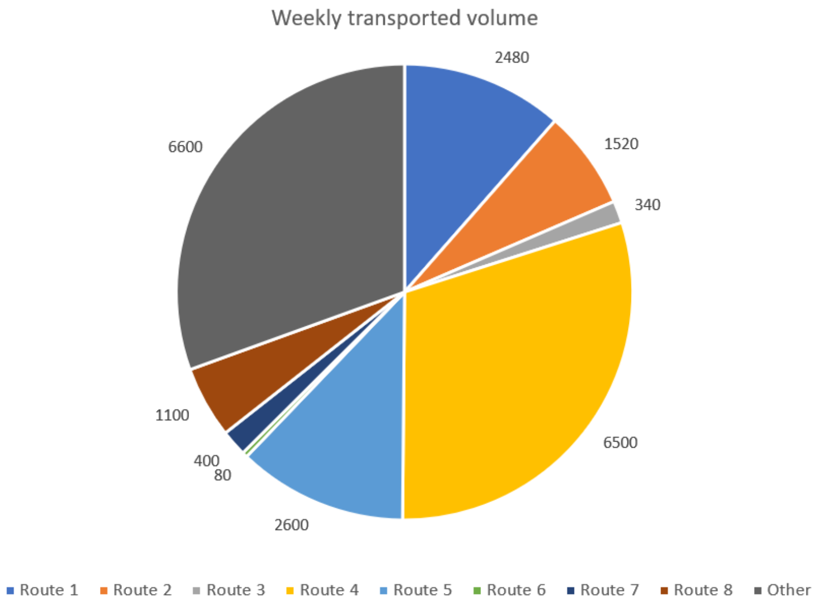

Figure 16: Routes volume distribution

In this chapter, the sub-research question below is answered. These findings will be used to answer the remaining research questions in upcoming sections.

RQ 7: What are representative supplier routes within the case study?

6.3.3 Nominal route scores

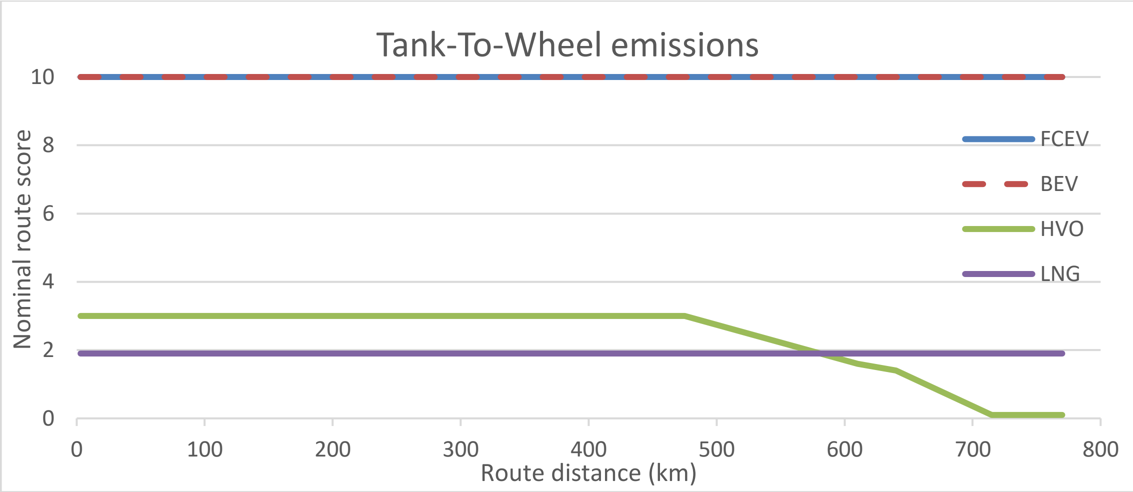

Figure 17: Route dependent nominal scores of Tank-To-Wheel emissions

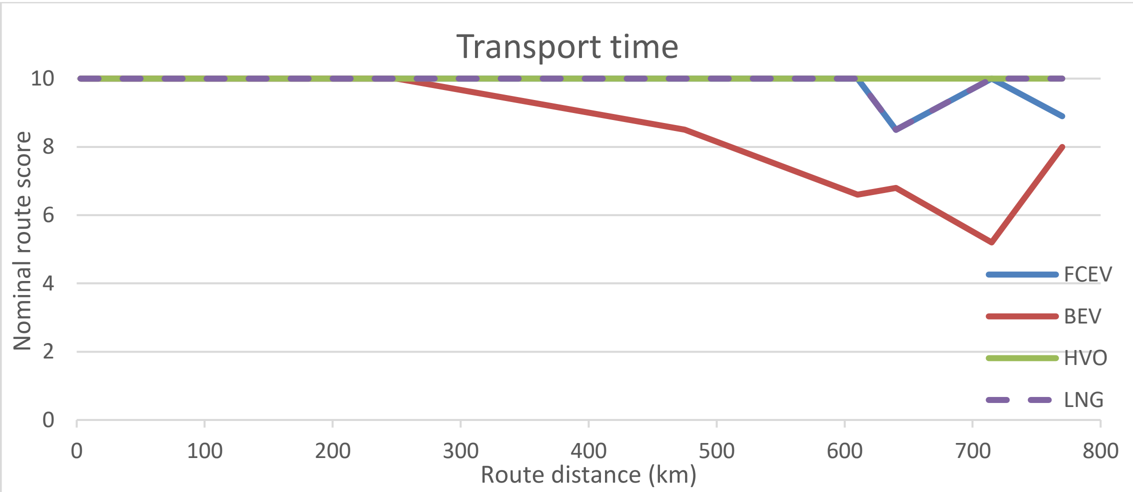

Figure 18: Route dependent nominal scores of transport time

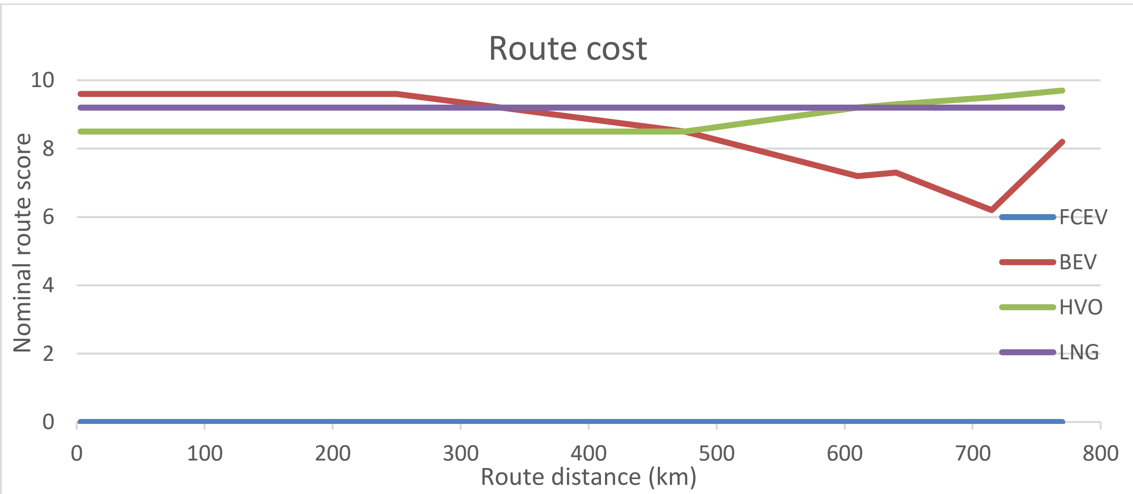

Figure 19: Route dependent nominal scores of costs

6.3.4 Key route findings

This section is based on an extensive elaborated route evaluation that can be consulted In the appendix. In this summary, the key findings from the eight routes are explained. These findings are crucial considerations in the adoption process of alternative fuels.

Hydrogen

When evaluating route 1 that originates in the UK, it became clear that flammable gas powered vehicles are not allowed to take the tunnel between the UK and France (Eurotunnelfreight, 2021). This implies the use of the ferry for hydrogen powered trucks, which will result in additional time. Furthermore, no additional burdens are expected when driving FCEV through the UK due to a sufficient infrastructure. Besides the UK, Germany has a sufficient infrastructure in most federal states. This makes most routes through Germany and highly feasible regarding hydrogen. The route from Poland starts near the national border of Germany. Therefore, this route might seem highly feasible as well. However, due a below average infrastructure in that area, detours are required to avoid risks. This implies additional costs and transport time. Some trips are even feasible without refuelling, the route from France through Belgium for example. Even when refuelling is required, only small detours are necessary. However, route 8 which is only a 3 kilometre trip, and which could suffice on a single tank, involves some burdens. In this area the refuelling infrastructure is limited. In other words, a truck designated to this route, needs to travel to Aachen, Eindhoven or Liege in order to refuel. However, this is not reflected in the scores of this route.

All in all, the hydrogen infrastructure needs improvement is some regions. However, for the state of innovation in which hydrogen trucks are in, the infrastructure is expected to reasonable sufficient In the near future. Especially when considering the 2030 predictions of the initial findings table (table 10), this alternative fuel seems to be highly feasible.

Battery electric

First of all, LSPs use price per kilometre as a business model. However, when BEV are implemented this could shift towards a price per time unit, due to the additional recharging time. Therefore, transport costs are expected to increase.

The infrastructure coverage of recharging station in Great Britain, Germany, Belgium and the Netherlands is sufficient for battery electric vehicles. However, eastern Europe and France lacks behind. Here is assumed that existing and upcoming recharging stations are suitable for battery electric trucks. However, if this actually could be the case in the 2023 is uncertain. Nevertheless, the BEV recharging infrastructure is ahead of its competition. Unfortunately, due to the limited driving range, most routes involve two recharging moments. Some of them can be combined with the obligated breaks. This limits the relative time loses. This explains the large transport time score elevation around the 770 kilometre mark. Here, a third break is obligated, which further decreases the relative time losses.

HVO

HVO is currently only publicly available in the Netherlands with regard to the countries that this route runs through. However, there are companies who supply HVO upon request in those countries. This seems to make implementation hard at first. However, converting regular diesel pumps to suit HVO requirements can be done without large costs, therefore making scalability easy. Due to mix ratios with regular diesel, the all trips are considered to be feasible. However, assuming a truck would tank HVO100 in the Netherlands and drives to the supplier, only a section of the total route is driven on HVO, the other part need to be powered by diesel. In some cases only 22% of trip can be powered by HVO. This causes large fluctuations in the scores. The scores of Tank-To-Wheel emissions decline the longer the trip is, as diesel pollutes more. Therefore, the maximum potential of reducing green-house gasses is not reached on longer trips. However, this causes also (positive) effects on the route costs. As prices of diesel are lower, the total route costs decline the longer the trip is. At last, as refueling procedures are similar to diesel, transport time is not affected on all eight routes.

LNG

Similar to hydrogen, LNG powered truck are not allowed to take the train between the UK and France. This is due to strict safety regulations. This causes the dip in transport time scores around the 615 kilometre mark. Fortunately, the LNG refuelling infrastructure across Europe is well build. France is an exception on this statement. However, due to the close proximity to the Belgium border of the cluster in question, no implications are present. In other words, the implementation of LNG powered trucks on the remaining seven routes, doesn't involve any other implications other than the ones found in the initial findings table (table 10).

6.4 Score results

This section will provide the route specific results with regard to each alternative fuel. By doing so, sub-research question 8 is answered. These overall result contain all of seven evaluation criteria and are weighted according to the Best-Worst method.

RQ 8: How do the alternative fuels perform when applied to the routes?

In this chapter, stream 1 of the conceptual model of this research will be completed. Here, the theoretical most suitable alternative fuel in a JIT/JIS supply chain will be found, according to 2023 predictions of the literature.

Resulting from the eight evaluated routes, the average scores can be consulted in the table 17. It should be mentioned that this average as stated there, is the average over the eight routes. In other words, it is not related to transported volume or driving distance segments. Here, battery electric trucks (BET) are the overall winner with LNG as a close runner up. However, as argued before, some fuels are more suitable for specific route characteristics compared to others (see figure below).

Table 17: Score results

		Route number	8		5		7		6		2		1		3		4				
		Route distance	3		180		250		475		610		640		715		770		Average nominal	Average weighted	Final score
		Criteria weights	Nominal	Weighted	Nominal	Weighted	Nominal	Weighted	Nominal	Weighted	Nominal	Weighted	Nominal	Weighted	Nominal	Weighted	Nominal	Weighted			
	Tank-To-Wheel emissions	0,11	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	
	Noise emissions	0,06	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	
	Truck performance	0,17	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	
FCEV	Transport time	0,19	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	8,5	1,63	10,0	1,92	8,9	1,71	9,7	1,85	6,56
	Energy availability	0,09	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	
	Costs	0,29	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	
	Fuel price stability	0,08	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	
	Route score		7,9	6,62	7,9	6,62	7,9	6,62	7,9	6,62	7,9	6,62	7,6	6,34	7,9	6,62	7,7	6,41			
	Tank-To-Wheel emissions	0,11	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	10,0	1,15	
	Noise emissions	0,06	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	10,0	0,59	
	Truck performance	0,17	9,0	1,51	9,0	1,51	9,0	1,51	9,0	1,51	9,0	1,51	9,0	1,51	9,0	1,51	9,0	1,51	9,0	1,51	
BEV	Transport time	0,19	10,0	1,92	10,0	1,92	10,0	1,92	8,5	1,63	6,6	1,27	6,8	1,30	5,2	1,00	8,0	1,53	8,1	1,56	8,37
	Energy availability	0,09	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	7,0	0,64	
	Costs	0,29	9,6	2,82	9,6	2,82	9,6	2,82	8,5	2,50	7,2	2,12	7,3	2,15	6,2	1,82	8,2	2,41	8,3	2,43	
	Fuel price stability	0,08	6,0	0,48	6,0	0,48	6,0	0,48	6,0	0,48	6,0	0,48	6,0	0,48	6,0	0,48	6,0	0,48	6,0	0,48	
	Route score		8,8	9,12	8,8	9,12	8,8	9,12	8,4	8,51	8,0	7,76	8,0	7,83	7,6	7,20	8,3	8,32			
	Tank-To-Wheel emissions	0,11	3,0	0,34	3,0	0,34	3,0	0,34	3,0	0,34	1,6	0,18	1,4	0,16	0,1	0,01	0,1	0,01	1,9	0,22	
	Noise emissions	0,06	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	0,0	0,00	
	Truck performance	0,17	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	
HVO	Transport time	0,19	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	7,65
	Energy availability	0,09	6,0	0,55	6,0	0,55	6,0	0,55	6,0	0,55	6,0	0,55	6,0	0,55	6,0	0,55	6,0	0,55	6,0	0,55	
	Costs	0,29	8,5	2,50	8,5	2,50	8,5	2,50	8,5	2,50	9,2	2,70	9,3	2,73	9,5	2,79	9,7	2,85	9,0	2,63	
	Fuel price stability	0,08	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	
	Route score		6,5	7,64	6,5	7,64	6,5	7,64	6,5	7,64	6,4	7,68	6,4	7,69	6,2	7,60	6,3	7,66			
	Tank-To-Wheel emissions	0,11	1,9	0,22	1,9	0,22	1,9	0,22	1,9	0,22	1,9	0,22	1,9	0,22	1,9	0,22	1,9	0,22	1,9	0,22	
	Noise emissions	0,06	1,2	0,07	1,2	0,07	1,2	0,07	1,2	0,07	1,2	0,07	1,2	0,07	1,2	0,07	1,2	0,07	1,2	0,07	
	Truck performance	0,17	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	10,0	1,68	
LNG	Transport time	0,19	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	10,0	1,92	8,5	1,63	10,0	1,92	10,0	1,92	9,8	1,88	7,94
	Energy availability	0,09	8,0	0,73	8,0	0,73	8,0	0,73	8,0	0,73	8,0	0,73	8,0	0,73	8,0	0,73	8,0	0,73	8,0	0,73	
	Costs	0,29	9,2	2,70	9,2	2,70	9,2	2,70	9,2	2,70	9,2	2,70	9,2	2,70	9,2	2,70	9,2	2,70	9,2	2,70	
	Fuel price stability	0,08	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	8,0	0,64	
	Route score		6,9	7,97	6,9	7,97	6,9	7,97	6,9	7,97	6,9	7,97	6,7	7,68	6,9	7,97	6,9	7,97			

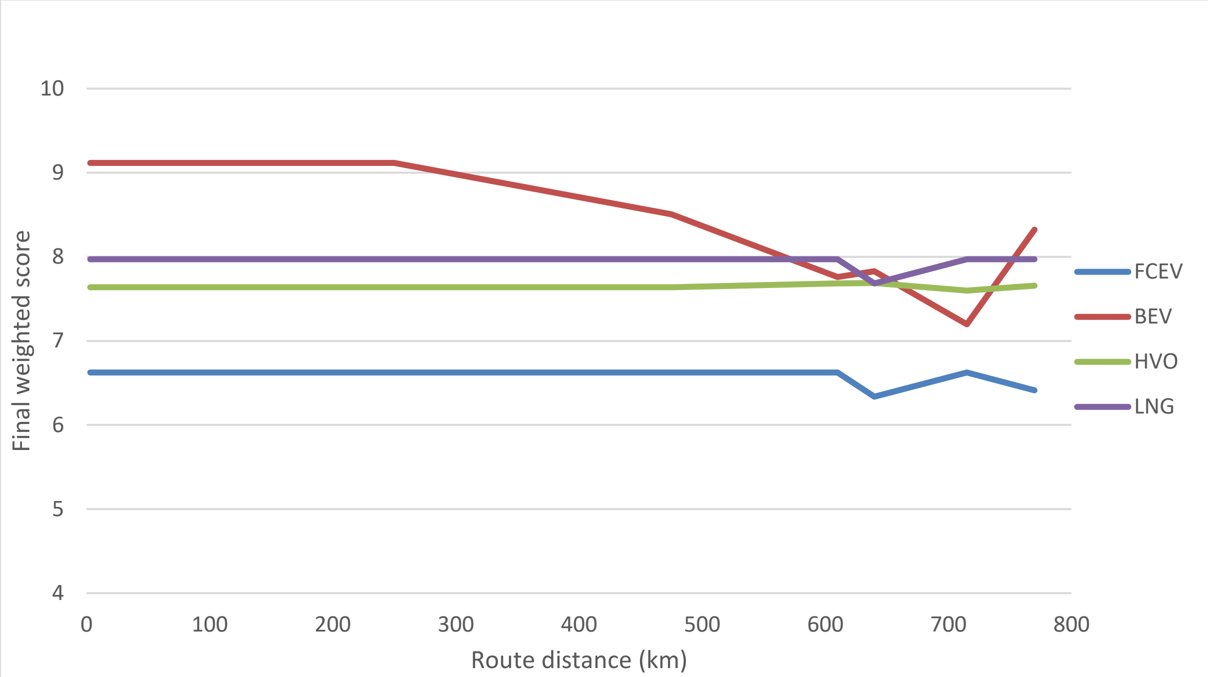

Figure 20: Feasibility ranking using average weighted scores relative to driving distance

Considering FCEV, an overall consistent score is found across most routes. however, one route causes a small dip in performance. That route originates from the UK and implies the channel crossing. Unfortunately FCEV are not allowed to use the tunnel and are therefore obligated to make the crossing using the ferry. This results in additional transport time, hence the dip around the 615 km mark. Furthermore, approaching the 800 km mark, a dip in performance can be observed as well. From this point and further, the hydrogen refuelling infrastructure is limited. Especially in eastern European countries. Therefore, scores are expected to decline even further after the 800 km mark. An explanation for the overall low score of FCEV, originates from the high fuel costs. An interesting question is: What needs to happen before FCEV is considered to be the overall winner in the feasibility ranking of stream 1? According to this model, this occurs when hydrogen fuel prices reach 3.48 euro/kg. Currently, this is 10 euro/kg. Consulting expectations from Weeda (2019), Oostdam (2019) and McKinsey (2010), who state prices of 0,50 euro/kg, less than 1 euro/kg and 0,08-0,77 euro/kg respectively in the near future, this fuel is likely to become the dominant innovation according to this model.

The battery electric truck is considered to be the overall winner in the feasibility ranking of stream 1. This is due to relatively low additional costs that is heavily weighted in this model. It should be mentioned that in this model fairly optimistic values and a highly efficient use of the battery electric truck is assumed. An interesting finding is the increase in score between the 750 and 800 km range. This is due the extra obligated break of the driver. Therefore, relative time losses can be kept to a minimum if recharging can be combined with the breaks. To make this achievable, recharging stations need to reach capacities so that every truck has a recharging point available without waiting time. Another boundary condition is the requirement of minimum driving range. If battery electric trucks could have a driving range of at least 360 km, assuming an average speed of 80 km/h and 4,5 hour work duration, efficiency of these type of trucks can be increased tremendously. This in turn, reduces additional costs and minimises relative time losses. However, this is not considered to be feasible in the near future. This feasibility is even questionable in the far future.

HVO seems to be in the midrange of the field and is fairly consistent across the eight evaluated routes. The fact that this fuel can be implemented in most existing Euro 6 engines makes the conversion easy. However, the factors that causes the third place of this fuel are the costs associated with this fuel. This is due to the relatively high fuel price. As future price movements are uncertain, it is difficult to predict how feasible this innovation is in a wider timeframe.

As runner up in the feasibility ranking of stream 1, LNG performs exceptionally well, even though the low emission reductions. This is due to a well implemented infrastructure and a minimum cost increase. However, similar to FCEV, LNG is not allowed the use the tunnel when crossing the channel to the UK. This explains the dip in figure 20. Furthermore, LNG is according to this model a suitable alternative. However, it should be noted that this is caused by the financial incentives when refuelling. These incentives are not infinite and are expected to be lifted in the future. That implies some risks when this type fuel is fully adopted.

7 Logistic service providers' view on fuel transformation

Previous chapters all worked towards completing research stream 1 from the conceptual model. This chapter will tackle research stream 2 (see figure 21). Here, logistic service providers are asked how they see the transformation of their truck fleet towards a more sustainable one (see sub-research question 9). Four managers from four different logistic service providers were interviewed and were shown the results of stream 1 after they explained their companies vision and expectations. The reason for using that order, was to refrain them for being influenced by the results of stream 1.

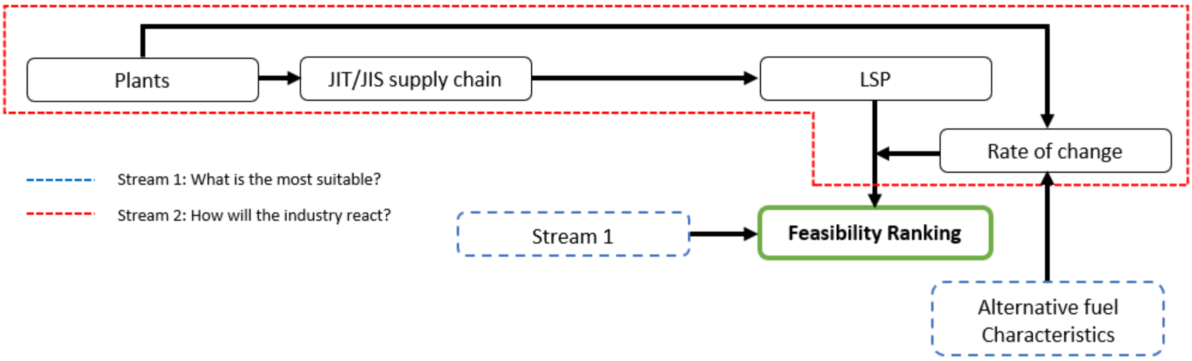

Figure 21: Conceptual model stream 2

RQ 9: How do logistic service providers see the transformation towards sustainability?

7.1 Individual findings

Ewals Cargo Care - J. Everts

Everts (2021) explained that Ewals already started the implementation of alternative fuels in other applications. They have implemented two LNG powered trucks in Germany in early 2021 and they have 25 HVO powered trucks operational dedicated to one specific client.

When discussing LNG trucks he explained that they are currently only an interesting alternative due to the MAUT exemption in Germany. That is why the two implemented trucks are used on German highways. A negative aspect is the fact that the MAUT exemption is only temporary and involves some future risks. Furthermore, they experienced some reliability issues of LNG refuelling stations. Nevertheless, he stated that when a client demands the implementation of LNG trucks, they are ordered tomorrow and operational within 5 to 6 months.

When discussing HVO he stated up costs of around 7 or 8 cents per km. This is inline with the initial findings table in section 6.1. He explained that if the clients demand the implementation of HVO, they can complete a 100% transformation the next day, as long as the client is willing to pay the up costs.

Considering Battery electric powered trucks, Everts (2021) stated that on paper these trucks have potential. However, the large amount of additional burdens and boundary conditions that need to be met to implement such type of fleet causes a large obstruction in the adoption process. Therefore, he expects that these type of trucks are limited to rigid trucks, city trailer applications or shuttle transport. In other words, in a JIT/JIS supply chain other fuels are more likely to become dominant.

Everts (2021) had in this interview high expectations of hydrogen fuelled trucks. He expects to have the first low-deck FCEV heavy-duty tractor operational in 2025. He emphasized the importance of a minimum required range of around 500 km before implementation is considered. However, he argued that trucks with larger ranges potentially lose their night cabins, due to larger tanks. This causes extra costs due to hotel expenses or it limits these trucks to day trips.

In general, he considered LNG as a precursor of hydrogen as they have similar refuelling characteristics. Therefore, they are testing with LNG to gain knowledge and acquire experience to eventually implemented hydrogen powered trucks on a wide scale.

Duvenbeck – A. Schlüter

Schlüter (2021) explained that Duvenbeck has limited experience with alternative fuels. However, they run 12 LNG powered trucks in Saarland with the aim to extend their LNG fleet with an additional 26 trucks. These trucks are implemented for short-haul city transport and are hauling gearboxes. However, they concluded that LNG is not efficient in city transport applications. Unfortunately, Duvenbeck has no experience or knowledge regarding the other alternative fuels.

Schlüter stated that Duvenbeck doesn’t have future objectives to make their transports more sustainable. However, he mentioned that: if a client agrees upon a minimum of a 5 year contract they are willing to extend their LNG fleet. The minimum of 5 years originates from their 100% return on investment horizon. In that same contract, a clause will be included that if events like the cancelation of the MAUT exemption occur, that up cost will be allocated to the client. Thereby averting risks. Nevertheless, he states that if a client approves those terms, they can implement a LNG fleet within six months after signing.

Schlüter (2021) explained that Duvenbeck doesn’t adopt sustainability related objectives because there are too many variables (infrastructure, clients, transported goods etc). Therefore, they are reserved regarding this transformation. A colleague of Schlüter argued that he doesn’t expect hydrogen or battery electric powered trucks in their fleet for at least the next 10 years. They rather focus on increasing efficiency of their Euro 6 and upcoming Euro 7 trucks and training their drivers.

Transimeksa – T. Ribalet

Ribalet (2021) elaborated that Transimeksa is relative reserved regarding the implementation of alternative fuels. This is due their competitive strategy, they try to offer the most reliable supply chain with the lowest cost. An alternative in such system could impact reliability in a negative way. Furthermore, an increase in costs are inevitable. Nevertheless, Ribalet explained that Transimeksa has a small fleet of LNG powered trucks operational in the area of Munich. These trucks are designated to a certain (short) route and therefore large uncertainties are taken away. However, during this implementation, they found some interesting results. The maintenance frequency of LNG trucks is higher than that of diesel powered trucks. Furthermore, due to the relative small market of these trucks, flexibility regarding on-road breakdowns is low. Moreover, in some cases LNG trucks aren't able to decouple the trailer when a breakdown occurs. That means that a potential substitute tractors isn't able to continue the trip (Ribalet, 2021). Another drawback of LNG trucks is the fact that the second-hand market isn't existing yet, therefore there are large uncertainties regarding depreciation. In other words, in order to avoid risks, Transimeksa depreciates LNG trucks down to zero euro, which is translated in a higher kilometre cost (Ribalet, 2021).

Ribalet (2021) explained that when companies demand the implementation of LNG trucks in their supply chain, this is feasible on some routes. This is due to a well build infrastructure in most regions. However, the reliability of the transportation activities can't be ensured by Transimeksa, due to the uncertainties regarding maintenance. At last, he mentioned that such implementation would take between 5 to 6 months.

Ribalet (2021) expects "huge changes", regarding alternative fuels, in the upcoming 2 to 3 years. He explained that in the last 8 months more progress has been made, regarding LNG trucks, than in the 5 years before that combined. However, he couldn't predict which fuel has the potential to become the dominant innovation. Furthermore, he explained that future developments are highly dependent on governmental incentives or subsidies. Therefore, Transimeksa is waiting with a widescale transformation until most uncertainties are taken away. Moreover, the demand for sustainable transport isn't high, especially in the market in which Transimeksa is in. In other words, logistic service providers aren't "pushed" to implement a more sustainable truck fleet.

Elflein – S. Butz

Butz (2021) stated that Elflein is open for change regarding alternative fuels. Elflein already implemented more than 40 LNG powered trucks and even did experiments with a custom made low-deck battery electric truck for plants owned by BMW. However, these test weren't positive. A too hot or too cold climate affected the performance tremendously. Therefore, and amongst other issues, Elflein did not continue to use this battery electric truck. Unfortunately, HVO is relatively unknown in Germany with a close to zero infrastructure. In other words, Elflein was not able to provide insights regarding this alternative fuel.

Fortunately, Butz was able to provide a lot of information regarding LNG powered trucks. He explained that Elflein uses LNG trucks on predefined routes designated the specific customers. However, contrary to Transimeksa, Elflein only implements this alternative fuel on long routes. This is due to fact that the more highway kilometres are driven to more benefits you get from the MAUT exemption. This in turn reduces costs. However, they found some important factors to consider regarding LNG. First, maintenance is unpredictable and more costly. Second, where truck manufacturers state driving ranges between 1000-1100 km, Elflein experienced ranges of only 650-750 km. At last, due to an increase of LNG trucks on the road and a slower rate of increase of refuelling stations, Elflein found in some cases that drivers needed to wait for 4 hours before a refuelling station was available. Especially, in a JIT/JIS supply chain this is unacceptable. When asked about the rate of implementation, Butz (2021) explained that currently LNG trucks are delivered from the factories in between 6 to 9 months. As at that point, the confirmed MAUT exemption period is relative short, he argued that such implementation is not efficient. This is due to the large uncertainties regarding the period after that.

At last, Butz (2021) stated similar objectives as Ewals Cargo Service. He explained that the managing partner has the objective the use LNG powered trucks as a “bridge technology” in order to gain knowledge and experience with regard to gaseous fuels. He expects the first hydrogen trucks in his fleet in 8 to 10 years (Butz, 2021). With the goal to implement a large fleet of hydrogen powered trucks at some point.

7.2 Overview

All in all, one can see that some logistic service providers are a bit reserved regarding alternative fuels and others try to be progressive. Despite some indifferences, most logistic service providers seem to prefer LNG powered trucks on the short-term when most uncertainties are countered. These uncertainties seem to be crucial in the adoption process. When looked at a wider timeframe, the more “progressive” logistic service providers tend to move towards a large hydrogen powered fleet. However, in this adoption process similar uncertainties are likely to occur, which could obstruct the rate of adoption.

When comparing the results of both streams, one can clearly see the distinction between the theoretical and practical approach (See table 18). Although, BEVs seem to be first in the feasibility ranking of stream 1, stream 2 is rather negative regarding this alternative fuel. However, both streams seem to recognise the potential of FCEVs in the long-term.

Table 18: Stream comparison. * Not quantitative substantiated

		Stream 1	Stream 2			
	Route length		LSP 1	LSP 2	LSP 3	LSP 4
Short-term	Short	BEV	HVO/LNG	-	LNG	-
	Long	BEV/LNG	HVO/LNG	LNG	-	LNG
Long-term	Short	FCEV*	FCEV	-	-	FCEV
	Long	FCEV*	FCEV	-	-	FCEV

8 Discussion

In this chapter will be reflected upon this thesis and its generalizability of the results. Besides that, the link with the master program "Management of Technology" will be explained. At last, both the scientific and the managerial contribution of this thesis will be stated.

8.1 Reflection

8.1.1 Reflection on the data

One of the largest drawback of this research is the limited (still relevant) literature available. Therefore, a considerable amount of grey literature is used in order to complete the data. This grey literature mostly consisted of published documents of truck manufacturers or articles related to certain events. In order to create scientific validity, more scientific literature is required. Moreover, even after consulting grey literature, some parameters were still unknown. Quantitative data of energy availability, for example, was not available. Although, this is considered an important evaluation criteria by decisionmakers. Besides that, the data found in literature deviates largely. That made it difficult to determine the reliability and relevance of this data. On top that, most data is highly uncertain. That could main that within a short period, this thesis might become obsolete and out dated. Especially when considering the rate in which innovations are developing currently. One way to counter most uncertainties could be to consult truck manufacturers for future expectations. However, it is likely that most knowledge or data is confidential.

8.1.2 Reflection on the methodology

Due to the limited time frame of this research, there is chosen for interviewing a limited number of three decision-makers within one case study with regard to determining the evaluation criteria. Additional cases or interviewees might result in different evaluation criteria. For example, if decision-makers would consider green-house gas emission an evaluation criteria rather than the subrange of emissions of Tank-To-Wheel, this would have a large impact on the results. Most likely, HVO might become the best performing alternative fuel due to the smart allocation of green-house gas emissions (90% reduction (OrangeGas, 2021)). Moreover, it is likely that the scores of FCEV and BEV would decrease drastically due to higher Well-To-Tank emissions.

One could argue if a cost-benefit analysis wouldn't be a better fit for this type of research. However, the use of the BWM creates to opportunity to see to what extend corporate environments are willing to transform towards a more sustainable way of doing business. Moreover, determining a monetary values for evaluation criteria such as TTW or noise emissions, is difficult and results would become hard to generalize.

An aspect that ensured the high applicability of the results, is the use of the case study. However, such case studies make it more difficult to generalize results and makes the reliability questionable. That's why the results of stream 2 are important, as those are not only relevant to the case study. Nevertheless, the generalizability and reliability of the stream 1 findings are discussed in the next section.

Fortunately, the conceptual model is an insightful guideline for companies who want to make their transport activities more sustainable. Moreover, this conceptual model can be used in other applications by simply changing the "JIT/JIS" square to other supply chain strategies. That makes this conceptual model usable in a wide range of industries. Where most research is limited to stream 1, here, an interesting finding are the LSPs' view on this transformation. Scientific literature, often neglects these practical approaches, although this is crucial in the adoption process of innovations. One could argue that applying similar research methods to stream 2 as used in stream 1, would provide some interesting results which could be compared easily. However, due to the time constraints of this research there is chosen for the research methods as explained in chapter 2.

One can clearly see a conflict in results of both streams of research. This can be explained through the fact that the theoretical approach (stream 1) doesn't account for unforeseen situations. These situations only come to light by field testing these innovations (i.e. a practical approach). This emphasises the importance of adding stream 2 to this research.

By combining both streams of research, the possibility for a well substantiated recommendation for companies in the automotive sector arose (see next chapter). Referring to the problem statement provided by VDL Nedcar, this thesis offers a "complete package" for companies who want pursue sustainability related objectives with regard to heavy-duty transport within JIT/JIS.

8.2 Generalizability of the case results

8.2.1 Evaluation criteria and weights generalizability

Both the evaluation criteria and their respective weights are extracted from the case study. This might imply a limited generalizability and reliability of the results. However, due to the fact the findings are extracted from several different decision-makers from different departments, it is expected that these results represent the industry well and accurate. Nevertheless, if multiple cases were applied, slight differences in the evaluation criteria and their respective weights might occur. Moreover, a JIT/JIS supply chain is more or less straight forward. In other words, different companies experience similar implications with regard to JIT/JIS. Nevertheless, the scores related to the evaluation criteria might differ between companies, as will be explained in the next section.

8.2.2 Routes generalizability

The scores of the evaluation criteria with respect to the routes might differ between companies. Moreover, the routes itself are hard to generalize due to the fact that different companies use different routes. However, the routes that are evaluated, represent a certain area which can be used as an insight for other companies in the industry. In this section will be evaluated to what extend other companies are able to use the results of the route related scores.

First of all, by using supplier clusters, a higher amount of automotive suppliers can be covered with fewer routes evaluations, without losing reliability and generalizability of the results. Furthermore, the eight routes that are evaluated are extracted from the case study. However, There are a total of 91 passenger car manufacturing plants located in the Europe, from which VDL Nedcar is a part of. These manufacturing plants are struggling with similar problems or will run into them into the near future. To provide an insight which manufacturing plants are able to use the results of these eight routes, and apply it to their specific case, are highlighted in the figure below. In this highlighted area, 56 plants are located (ACEA, 2020) who should be able to use the results from this research to make their business more sustainable. In other words, 62% of the European passenger car manufacturing plants could benefit from the result of this research. However, it could be argued that a percentage of these plants do not use a JIT/JIS combined with Warehouse-on-Wheels supply chain strategy. Nevertheless, these findings can provide an insight in the transformation towards sustainability. Furthermore, besides the passenger car market, there are also light commercial vehicle plants (11), heavy-duty vehicle plants (14) and bus manufacturing plants (12) covered with the findings of these routes (ACEA, 2020). Again, some of these plants probably do not apply the exact supply chain strategy as discussed before. However, they are able to use these results as an insight in their transformation.

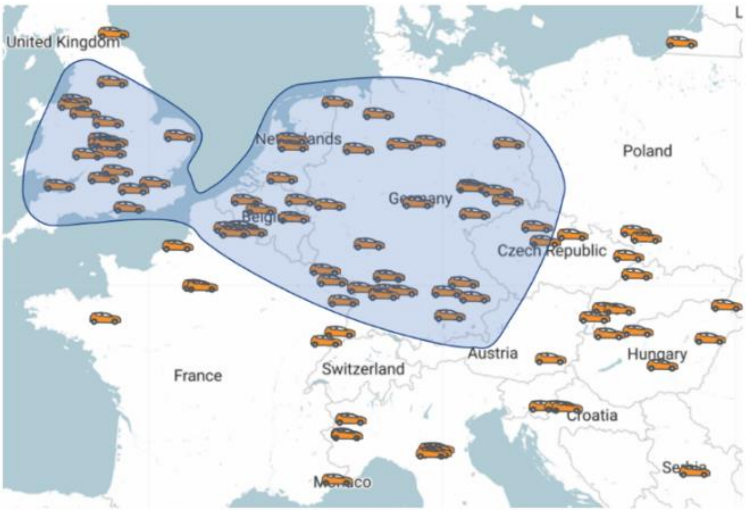

Figure 22: Passenger car manufacturing plants in Europe. Modified from ACEA (2020)

8.3 Link with master program: Management of Technology

Best-worst method is taught in course MOT9591 technology battles (elective). In this course is explained how to determine the factors that will influence adoption or domination of an innovation and to what extend by applying the Best-Worst Method. In other words, this research can be considered a technology battle in which the method is applies as taught in MOT9591. However, in this research, this is placed in a corporate decision-making context rather than an overall innovation evaluation. That implies the involvement of course MOT1452 inter- and intra-organisational decision making. Furthermore, this research is highly related to the course MOT2421 Emerging and breakthrough technologies as most of these alternative fuels are in an early or developing stage of life.

8.4 Contribution of this thesis

Scientific

During the course MOT2004 Preparation for the Master Thesis, it became clear that alternative fuels in heavy-duty transport are mostly individual researched in existing literature. That makes it difficult to compare alternative fuels to each other. Furthermore, the researches that made some comparisons, were highly generalized and therefore hard to apply to specific situations such as in the automotive industry. Thus, the scientific contribution of this thesis is threefold: (i) a conceptual model has been made that creates a theoretical "guideline" for companies in the automotive sector to determine their most suitable alternative fuel and adjust their sustainability related objectives accordingly. (ii) Using the findings of the routes, local refuelling infrastructure is evaluated. This provides an insight in the rate of developments with regard to certain geographical locations. (iii) Including the objectives and views of logistic service providers on this matter, created the possibility to define a substantiated prediction on how the market will react to this transformation and at what rate.

Managerial

By combining both streams of research, decisionmakers within the automotive industry are able to create well substantiated and reachable objectives on how to tackle the climate change and to what extend they are able to contribute to that. Furthermore, the conceptual model that has been established creates a stepwise decision-making structure in order to adjust this problem to their specific situation or application. Furthermore, all information that is required for completing a company specific analysis, can be found in the initial findings table or in the appendix, making this thesis a complete "package" for the industry.

9 Conclusion

At this point all sub-research questions are answered by following the two streams of research. However, the main research question still needs to be answered. This will be done by combining the results of both research streams.

Main research question: What are feasible alternative fuels in European heavy-duty transport when a JIT/JIS supply chain strategy is applied?

The results of stream 1 show Battery Electric Trucks (BETs), on average, as the best fit in a JIT/JIS supply chain. This is mainly due to the lowest cost with respect to the other alternative fuels. However, this is still 0,02 euro per kilometre more expensive than diesel in equal business models. With respect to the routes can be seen that at shorter driving distances BETs perform exceptionally well. However, at longer distances the implication of long recharging times start to show. An interesting finding regarding these longer driving distances is that: if BEVs could reach driving ranges of at least 360 kilometre, relative time losses are kept to a minimum. This creates the ability to drive between the obligated breaks without recharging. Nevertheless, at these longer distances LNG seem to be the best fit. However, the future of LNG powered trucks are uncertain after 2023 as financial incentives are unconfirmed. Therefore, HVO might seem a suitable alternative. However, decisionmakers should consider a limited availability and a large amount of additional fuel costs. Fortunately, the conversion from diesel to HVO is very easy. This makes the short-term feasibility of this fuel relatively high. At last, hydrogen is considered. Due to high fuel costs, hydrogen scores the lowest. However, with the long-term fuel price predictions, this fuel could become interesting alternative in the future.

Research stream 2 shows results that are disturbing regarding the ongoing transformation. Up to this day, some logistic service providers (LSPs) are not involved or interested in the transformation towards more sustainable transport. The LSPs that do consider alternative fuels on a large scale, tend to have a preference for LNG in the short-term. This is mainly due to extensive (mostly positive) experiences through field testing. HVO seemed to be unknown by LSPs and they were relatively reserved. Most, LSPs expressed their opinions and expectations for BEVs rather negatively. In general, they don't expect to implement battery electric trucks in their fleet at all. In other words, although the BEV seem to be best fit in a JIT/JIS according to the 2023 expectations, it is unlikely that this will become reality. Regarding hydrogen powered trucks, most LSPs were rather confident about these FCEVs and expect to add these type of vehicles to their fleet in the future. Especially when considering the 2030 expectations from the initial findings table, the hydrogen truck seems to be the future of heavy-duty transport within JIT/JIS.

An interesting finding is the difference in results of both streams of research. Where stream 1 states battery electric trucks as most feasible, stream 2 tends to prefer LNG (short-term) or hydrogen (long-term) powered trucks. In other words, one can see a significant difference between the theoretical approach and the more practical approach.

All in all, the future looks bright for hydrogen powered trucks. However, just like most innovations, it has still a long way to go. As can be concluded from the Best-Worst Method, costs is the most determining factor regarding alternative fuel adoption in JIT/JIS. To what extend an alternative fuel reduces emissions isn't determinative. Moreover, besides cost, every day usability criteria such as, transport time and trucks performance are more important than potential emission reduction. This is expected from corporate environments. However, it is a concern regarding climate change. From these findings, in combination with the "chain of influence" (figure 8), can be concluded that governments are crucial in accelerating the adoption of alternative fuels. This is due to large incremental costs that are heavily weighted in such evaluations. Although, incentives are announced (see initial findings table) what they include or for whom they are, is still uncertain.

10 Recommendation

10.1 Short-term recommendation for companies

If the automotive industry wants to make their transportation activities more sustainable in the short-term, it is advised to contact their Logistic Service Providers to implement some LNG powered trucks designated to predefined routes. These predefined routes will likely involve driving distances up to 350 kilometre, as the most uncertainties can be countered (the shorter the route, the more certain variables become). However, it should be noted that this is likely to be only a small percentage of their total transportation activities. Therefore, companies should see this small implementation as an experiment to gain knowledge and experience regarding refuelling procedures.

If companies in the automotive industry are willing to be an early adopter, it is advised to contact logistic service providers and truck manufacturers. Potentially, a cooperation between these three actors could result in the first low-deck Battery Electric Truck (BET). This truck could be used to drive on short routes, most likely up to a driving distance of 15 kilometre, to gain knowledge and provide this information back to the truck manufacturers. This short-term implementation should also be seen as an experiment that could potentially accelerate the overall adoption of battery electric trucks, regardless of its application. In other words, these experiments might reduce the result gap between the theoretical (stream 1) and the practical (stream 2) approach in the future.

10.2 Long-term recommendation for companies

As predictions of the literature and expectations of some logistic service providers made clear, hydrogen might become the dominant alternative fuel in a long-term view. Hydrogen performed exceptionally well regarding sustainability and technological related evaluation criteria. However, the economical perspective caused some implications. Therefore, it is advised to use knowledge gained, by implementing LNG trucks, to implement hydrogen trucks on a large scale when costs are reduced. Hydrogen “wins” in stream 1, when fuel prices of 3,48 euro/kg are reached. Therefore, that is considered to be the theoretical point from which stepwise implementation is advised. However, it is uncertain if this stepwise implementation is possible before 2025. Nevertheless, 2030 seems to be a feasible timeframe.

To put in perspective, if VDL Nedcar completes a 100% implementation of hydrogen powered trucks for all their transportation activities (not limited to JIT/JIS), this would reduce CO_2 emissions between 10,9 and 14,4 million kg per year (TTW). This is between 28%-34% of their total CO_2 pollution per year. In other words, the automotive industry could reduce their emissions by a large extend by making their transportation activities zero emission using hydrogen for example.

10.3 Recommendation for future research

An important criteria that couldn't be well substantiated in this research are the energy availabilities of all alternative fuels. To provide some extra validations, research regarding this topic is required. Moreover, this is not a problem limited to this research but could obstruct other research as well.

A way to create a higher degree of validity of the results can be obtained by consulting and interviewing truck manufactures. Experts within these companies can provide additional factors or problems to consider when adopting alternative fuels. Therefore, a follow-up research that includes the results of researches like this thesis and the findings of truck manufacturers is advised.

A topic that is not considered in this thesis is potential implementation costs. Some alternative fuels might require some changes in processes or infrastructure within companies. These potential implications need be to be well evaluated before large scale implementation. However, one could argue that these need to be shown by experimental adoptions.

As this thesis concluded that it is expected that hydrogen trucks are the future, companies might demand a timeline in which certain events are likely to occur. The expected first available low-deck hydrogen truck for example. This could provide the required information for companies to adjust or develop their sustainability related objectives accordingly.

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Appendix A: Alternative fuel characteristics

Sustainability perspective

Corporate organisations, such as VDL Nedcar, who seek to make their business more sustainable are only interested in Tank-To-Wheel emission analysis, as these are directly related to their business processes (chapter 5). Gasses that are categorized under Green-house gasses is an extensive lists. In this research there will be focusses on the gasses that are most common in emission evaluations. These are: CO_2, NO_x, CO, HC and PN. Carbon dioxide, nitrogen, carbon monoxide, carbon hydrogen and particle numbers respectively. Furthermore, the assumption will be made that the rate of innovation in LNG, biodiesel HVO and diesel will results in equal further reductions in emissions within similar timeframes.

Hydrogen

Hydrogen can be combined with oxygen in the electrochemical reactions of a fuel cell to produce electricity, a clean, versatile energy carrier. Fuel cells produce electricity with a potential efficiency of 60%; the electricity can be used directly converted to motion (Crabtree & Dresselhaus, 2008)

In a Tank-To-Wheel analysis hydrogen powered trucks emit no green-house gasses. During the conversion of this energy carrier towards kinetic energy, the only residual product is water (Crabtree & Dresselhaus, 2008).

Battery electric

Battery electric vehicles do not emit green-house gasses when driving. In other words, in a Tank-To-Wheel analysis a 100% reduction in emitted green-house gasses compared to diesel powered trucks can be obtained. Therefore, battery electric vehicles, just like hydrogen powered vehicles, are called Zero Emission Vehicles (ZEV). Which are heavily promoted by governmental organisations and environmental initiatives.

Biodiesel HVO

According to the literature, scientific test have been done to assess green-house gas emission of biodiesel HVO in a wide range of applications with promising results. Unfortunately, grey literature seems to be misleading as they often state that a CO_2 reduction is possible up to 90% in the case of HVO100 (OrangeGas, 2021) (DAF, 2021). Although this can be true in a Well-To-Wheel analysis, this is not possible in Tank-To-Wheel analysis.

HVO can be mixed with conventional diesel. This can be done in a wide range of mix ratios, from 20% HVO (HVO20) up to 100% HVO (HVO100) which is pure HVO. Existing refuelling stations often offer HVO20 and HVO100. However, there are non-commercial examples of variable mix refuelling stations (Goodfuels, 2021).

An American research investigated possible emission reductions using Cummins isx-15 and ISB6.7 engines which are used in heavy-duty applications in the USA (Karavalakis et al., 2016). However, these are hard to compare with European engines, truck size and loads. Therefore these reductions are stated in percentages compared to American diesel. Karavalakis researched the emissions using highway (long-haul) road-test what increases the applicability of the results to the case. An remarkable finding is the NO_x emissions, no significant reduction is found here due to large fluctuations in the test. Besides that, the number of PN significantly decrease. The values, as stated in the table, are approximations.

Table A1: HVO emissions reductions compared to diesel (Karavalakis et al., 2016)

HVO content	Δ CO_2 (%)	Δ NO_x (%)	Δ CO (%)	Δ HC (%)	Δ PN (%)	Δ average (%)
HVO20	-1	0	-81.8	-5	-80	-33,56
HVO50	-2,2	0	-	-74,3	-68	-52
HVO100	-4	0	-42,2	-62	-60	-33,64

HVO50 has to most promising results. However, the reliability of the values are questionable, due to a reduction larger than 100%. As most refuelling stations offer HVO20 and HVO100, there is chosen to use HVO100 for further calculations.

To validate the data above, other references are found. A research involving tests with personal vehicles on dynamometers without aftertreatment, concluded the following (Sugiyama et al., 2011):

Table A2: HVO emissions (Sugiyama et al., 2011)

HVO content	Δ CO_2 (%)	Δ NO_x (%)	Δ CO (%)	Δ HC (%)	Δ PN (%)	Δ average (%)
HVO20	-	0	-23,7	-31,3	-	-18,3
HVO40	-	0	-30,8	-37,5	-	-22,8
HVO100	-	0	-38,5	-56,3	-	31,6

The results of HVO20 and HVO40 deviate strongly compared to the results of Karakavalakis et al. However, the results of HVO100 confirm each other. Again, validating the choice of using HVO100 for further calculations. Besides that, this research concludes that HVO100 reduces most green-house gasses. A research done by Kuronen & Mikkonen in 2007 emission reductions of HVO20 of NOX 0%, HC -40% and CO -15%. For HVO50: NOX -5%, HC -50% and CO -23%. At last, HVO100: NOX -10%, HC -50% and CO -28%. According to Bohl et al., HVO blends up to 30% still comply with DIN EN 590 (Peters, et al., 2021)

LNG

A research performed by TNO tested emissions of a heavy-duty LNG truck (Vermeulen, 2019). They took a Volvo FH 420 LNG, which was introduced in 2018. This truck uses a so called HPDI technology and LNG storage. The results of this vehicle were reflected against older results from six diesel trucks from 2013. Measurements of the greenhouse gasses were performed. The results stated a reduction of 19% in greenhouse gas emissions for an average long-haul trip compared to the diesel baseline from 2013. For highway operations, the difference was even higher, which was up to 23% (Peters, et al., 2021). However, Peters et al. (2021) states some concerns regarding these tests: “The weak parts of this study are the comparison with older diesel technology and the measurements involving only one truck.”

Furthermore, another research, performed by Vermeulen as well, studied a 15,5 ton tractor-semi combination driven on motorways. He stated the following findings regarding the emissions of a LNG powered truck: 600 g/km of CO_2, NOX emissions were less than 0,025 g/km, +/- 1*10^11 #/km of PN and HC was tested to be less than 0,01 g/km (Vermeulen et al., 2017).

Volvo states CO_2 emission reductions, using their LNG application, of 20% (Volvo, 2021). This is similar to the Iveco Stralis Natural Power (IVECO, 2021) and Scania’s Natural gas application with 410 HP, which has a driving range of 1.600 km with two tanks (Scania, 2021). The motor is driven be pure natural gas using a spark ignition system. According to Scania, the engine emits up to 15% less CO2 than a comparable diesel motor (Peters, et al., 2021). It should be noted, that these specifications are published by the truck manufacturers. Therefore, these findings can provide an indication but should be labelled as less reliable.

A Tank-To-Wheel assessment has been performed, by Dunn et al. (2013), of the first-generation (HPDI) engine based on emissions analysis during transient and steady-state cycles. Dunn et al. explains that they did not perform a well-to-wheel analysis due to uncertainties regarding upstream emissions. During these tests, they found a reduction of 22,9% of CO_2 compared to similar diesel applications. The emissions found at the exhaust, mainly consisted of CO_2.

Another research, performed by Rosenstiel et al. (2014), evaluated a Tank-To-Wheel analysis as well. They based their findings on LNG powered trucks using spark ignition. They state that data availability was not sufficient for HPDI technology at that time. They concluded a slight emission reduction of 3,6% for the LNG powered truck compared to diesel equivalents.

Diesel

In this section diesel emission are described. This is done to provide a reference for the other fuels. The diesel references is limited to Euro 6 engines, which are most common nowadays. First of all should be mentioned that in the Euro 6 standard, CO_2 is not regulated. This is because CO_2 emission are fuel dependant.

Volvo states on their website that their euro 6 engines emit 0,9 g/litre of NO_x and 0,13 of g/litre CO. Furthermore, they state PM emissions of 0,01 g/litre and HC emissions of 0,06 g/litre. Following from the assumption that a typical 40 ton truck (tractor and semi-trailer) in long-haul transportation consumes between 29-35 litre per 100 km and the fuel quality standard, which is 2,6 kg CO_2 per litre diesel (EN590), the CO_2 per km van be calculated (Volvo trucks, 2018). This results in 1152 g/km CO2.

Mercedes states their diesel engines consume 19,44 litres per 100 km in a 40 ton combination, which results in 512 g/km of emitted CO_2 (Daimler, 2008). It should be noted that this test has been done to set a record in 2008. Therefore, these results do not seem to be reliable.

A research performed by TNO tested five diesel trucks using Euro 6 engines. The tests resulted in approximately 650 g/km CO_2 on motorway use with a 15,5 ton payload (Vermeulen, et al., 2017).

Which is similar to payloads used the car manufacturing industry (average of 12 ton). This is due to the fact this JIT/JIS parts are mostly highly volumetric

Table A3: Diesel emissions

Diesel emissions	(Grigoratos, et al., 2019)	(Vermeulen, et al., 2017)	(Volvo trucks, 2018)	(Vermeulen, et al., 2016)	Values for further calculations
CO_2 (g/km)	776	650	832	-	**650**
NO_x (g/km)	0,423	0-0,2	0,288	0.325	**0,2**
CO (g/km)	1,05	-	0,0416	-	**1.05**
HC (g/km)	0,13	0,02	0,0192	-	**0,02**
PM (g/km)	-	-	0,0032	-	**-**
PN (#/km)	$7{,}5*10^{10}$	$1*10^{11}$	-	-	**$1*10^{11}$**

Technological perspective

Hydrogen

Truck performance

First, hydrogen-based Fuel Cell Electric Vehicle (FCEV) trucks need to be evaluated performance wise.

Load length

In Europe, there are strict regulations regarding truck dimensions. These dimensions are fixed in height, width and length. Length includes the tractor maximum length, trailer maximum length as well as the maximum total length of the combination of tractor and trailer (Evofenedex, 2021). These rules make it challenging to incorporate the components in the tractor as one needs, among others a fuel cell, a fuel tank, a battery and an electric motor (Oostdam, 2019). Optimally, these components need to be placed in the trucks without compromising load lengths. However, mounting a fuel tank in a hydrogen truck is challenging. Given the low density of hydrogen, the fuel tank will be relatively large. It is estimated that roughly 1 m^3 stores 39 kg of hydrogen at 700 bar. At 300 bar, the same amount of kilograms will use approximately 1,6 m^3 (Oostdam, 2019). Furthermore, it is estimated that fuel tanks only have an efficiency of 80%-90% (Peters et al., 2021; Oostdam, 2019). This is due a minimum recuired pressure inside the tanks.

In current hydrogen trucks concepts, there are three possibilities for mounting a hydrogen fuel tank (Oostdam, 2019).

4. Placing the Hydrogen tanks directly behind the cabin. This requires multiple smaller tanks of approximately 5 kg which are stacked vertically. Nikola has adopted this concept and released a capacity of 34 kg (Nikola, 2019).

5. Placing hydrogen tanks in the side pods. This implies that the tanks are located between the first and second wheel axles. Diesel trucks mount their diesel in tanks at this location as well.
6. Placing the tanks in the trailer. This concept is a prototype truck that has been developed by VDL for the project Waterstofregio 2.0 (Oostdam, 2019). The project consists of creating a 44-ton electric tractor semitrailer with a hydrogen range extender. The truck can drive 100 kilometres on its battery, with the hydrogen range extender the driving range can be extended to 400 kilometres (Oostdam, 2019). However this would compromise load lengths significantly.

Load weight

Research shows that hydrogen trucks (tractors) weigh around 14 tons, which is similar to diesel powered trucks (Transport and Environment, 2020). In other words, no additional tractor weight is expected. Even if it does so, zero emission vehicles (ZEV) get exemption for additional load weight up to 2.000 kg, which will be explained later in this chapter. This would imply that load weights are not compromised.

However, Peters et al. 2021 explains that, concerning weight issues, due to the exchange of ICE and gearboxes by electric drivetrains leaves only 243 kg for the fuel cell system. For the calculation of the achievable driving range, they assumed the following efficiencies: 60% fuel cell system, 97% power electronics, and 95% electric motor. These assumptions would imply a tank-to-wheel efficiency of 55%. An assumed tank weight of 557 kg will allow maximum range between 338 and 646 km (Peters, et al., 2021). Again, the main challenge for hydrogen storage systems is the small volumetric energy density, as stated by Peters et al. Furthermore, they expect a load weight loss of 500 kg, which could be compensated with the ZEV exemptions.

Moreover, a study that assessed fuel cell systems, determined that the weight of hydrogen (tested at 5,6 kg capacity) is only 5% of the total tank weight at 700 bar. In a 350 bar configuration, this would be 6% of the total tank weight (Hua, et al., 2010). This results in a total tank weight (filled) of 112 kg at 700 bar. Extrapolating this linear, would mean a full tank weight 1.600 kg at 80 kg hydrogen capacity. However, real world applications are expected the weight less, due to more efficient tank shapes.

Zero emission vehicles (ZEVs) and near-ZEVs may exceed obligated gross vehicle weight limits by an amount equal to the difference of the weight of the (near-)ZEV powertrain and the weight of a comparable diesel tank and fuel system. This additional weight can be up to 2.000 kg. A ZEV is defined as a vehicle that produces no criteria pollutant, toxic air contaminant, or greenhouse gas emissions when stationary or operating conditions. A near-ZEV is a vehicle that uses zero emission technologies, uses technologies that provide a pathway to zero emission operations, or incorporates other technologies that significantly reduce vehicle emissions (Alternative Fuels Data Center, 2021).

Truck power

A few companies are developing hydrogen powered trucks. Unfortunately, the manufacturing process of these vehicles is in its early stages. Hyzon motors is such company. They claim that their heavy-duty trucks has 500 KW (Hyzon motors, 2021). Nikola advocates similar power outputs (Nikola, 2019). These values are similar to common diesel configurations as well.

Refuelling infrastructure

In 2019, there were only six hydrogen refuelling stations (HRS) operational with three additional stations in progress in the Netherlands (Neis, 2019). Currently, there are eight HRS available in the Netherlands and another four are planned to be built (orangegas.nl). There are multiple applications for subsidy to build an HRS, all are granted, however, expansion of this infrastructure is not sufficient. This is due to the limited demand for hydrogen refuelling infrastructure (Oostdam, 2019) which seems to be reinforcing each other. It is the ambition of the Dutch government to increase the number of hydrogen refuelling stations to 50 and have over 2 million hydrogen-powered vehicles by 2030 (Rijksoverheid, 2019). However, H2Platform tried to enforce the inclusion of the goal to have 50 hydrogen refuelling stations by 2025 in the climate agreement (H2Platform, 2021). Which would benefit the adoption rate of these vehicles.

Germany is leading with regard to a hydrogen refuelling infrastructure. There are 91 stations open and an additional 15 are in progress (H2.live, 2021). Unfortunately, the rest of Europe is lacking behind, with just a couple of stations per country. Which is not sufficient for international transport behind the borders of the Netherlands, Belgium and Germany and some parts of the Czech Republic, Swiss and Austria in the near future.

Air Liquide has the ambition to build hydrogen fuelling stations with a capacity of 2.000–4.000 kg hydrogen per day (Peters et al., 2021). They made plans for locations in France, Switzerland, Belgium and Germany as part of the project H2HAUL, and in the Netherlands for HyTrucks. In France, the first refuelling station for hydrogen trucks with a capacity of 1.000 kg hydrogen per day will be build. Later on, an additional four refuelling stations are planned. HyTrucks has the objective to build 20 refuelling stations, with a total capacity of 40,000 kg hydrogen per day by 2025 suitable for a 1.000 trucks (Peters et al., 2021).

A study, performed by Rose et al. (2020), examined the hydrogen refuelling station (HRS) infrastructure that is expected to be required by 2050, as well as the relation between such an infrastructure design and German power systems. In this research, it is assumed that onsite hydrogen production will become dominant. An important finding with regard to this study includes the number of hydrogen refuelling stations required. By making use of an infrastructure location planning model, the study determined that 140 HRS is expected to be sufficient to serve all German heavy-duty trucks.

Transport time

Refuelling time

When refuelling a hydrogen truck, there are several refuelling standards, which are 350 or 700 bar configurations. This chapter describes and compares these refuelling methods based on technical characteristics. The most important technical characteristic of a refuelling station is the refuelling speed. Ideally, heavy-duty vehicles would like to use high-speed fuelling stations. With diesel, normal refuelling speeds are around 60 litres per minute, whereas high-speed fuelling stations reach refuelling speeds up to 120 litres per minute (AVIA, 2018). Given a fuel tank size of 1.000 litres, this means that the refuelling process takes around 5-10 minutes. High-speed refuelling is also possible for hydrogen. However, such stations are not implemented yet (Oostdam, 2019).

Currently, the refuelling speed at regular HRS is around 1 to 1,5 kg/min. For heavy-duty trucks the J2601 HD describes that the maximum refuelling speed is allowed to go as high 7,2 kg/min at 350 bar (Schneider, 2012) and up to 8 kg/min at 700 bar (Fuel Cells Bulletin, 2019)

Nikola advocates that the refuelling time is approximately 10 to 15 minutes this would imply that the refuelling speed would be somewhere between 5 and 8 kg/min. The Nikola TRE truck type is expected to have a driving range of 500 to 1.200 km (Nikola, 2019) which would suggest a fuel tank capacity of 80 kg when an energy consumption between +/- 13 km/kg is assumed (Forrest et al., 2020).

All in all, the average refuelling time will increase with around 5 minutes which indicates an increase of 66%.

Driving range

Hyzon Motors claims a 400-600 km range in their 50 ton heavy-duty applications (Hyzon motors, 2021). However, In EU a maximum of 40 ton is allowed during standard transportation activities. This might lead to longer driving ranges on European roads. It should be noted, these values are expectations advocated by the companies who are about to sell these vehicles. Road test might conclude different driving ranges, as driving style etc. might influence these values.

Energy availability

Hydrogen can be extracted from fossil fuels and biomass, from water or from a mix of both. Natural gas is currently the primary source of hydrogen production, contributing to around three quarters of the annual global hydrogen production, which is approximately 70 million tonnes. This accounts for 6% of global natural gas use. Gas is followed by coal, due to its dominant role in China, and a small fraction is produced from the use of oil and electricity (Birol, 2019). Moreover, if future hydrogen supply relies on imports from remote locations with higher (renewable) energy yields, liquefied hydrogen storage could become the dominant standard, as the hydrogen would then be delivered in a liquid state by using ocean-going vessels (Peters, et al., 2021).

This means that, due to a wide range of production methods and transport possibilities, scarcity of hydrogen is not expected. However, evaluating it from sustainability perspective, the optimum production method is certainly using renewable energy (electricity). To refute, following from the corporate perspective, the production method is not an evaluation criteria for determining adoption potential. Therefore, all production methods can be considered.

Scientific research shows that the modern capacity of refuelling stations ranges from 120 kg/day to 1.500 kg/day (Hydrogen Council, 2017; Isenstadt & Lutsey, 2017). The largest fuel station size would allow 30 to 40 trucks to refuel a day, which is in the current situation sufficient. In other words, the availability of hydrogen is considered to be sufficient. However, production numbers need to increase when hydrogen transport is adopted to fulfil demand.

Battery electric

Truck performance

Load length

Looking at technical graphs of DAF CF, which are commercially available in battery electric configurations, load lengths are equal to equivalent diesel configurations (DAF, 2021). As batteries are often stored between the first two axles, It should be noted that the DAF CF as discussed has a 220 km driving range. The Tesla Semi truck, which has a driving range of approximately 800 km (Tesla, 2021), is not able to carry standard 13,6 m long mega trailers. This is due governmental restriction on maximum dimensions, which is in most countries of the European Union 18,75 meter (Evofenedex, 2021). Evaluating technical drawings of the Tesla Semi, a load length of approximately 1 meter will be lost. There are other examples of battery electric trucks, such as Volvo FE and the Mercedes-Benz EActros, however these are rigid trucks. This means they have more space between the axles to accommodate additional batteries to obtain an extended driving range. As discussed before, this research will focus on a tractor-trailer combination as this combination is used in a JIT/JIS strategy combined with a Warehouse-On-Wheels (WOW). Furthermore, it is important to note that the trucks as discussed do not have a low-deck, meaning that the mega trailers commonly used in the automotive industry cannot be towed by these tractor configurations due to height restrictions.

Load weight

It is often claimed that Battery electric vehicles need to account for reduced load weight capacity due to the significant weight of the onboard battery system. Depending on the battery pack's energy density and capacity, this is often to be the case, particularly with respect to modern day’s battery technology (Transport and Environment, 2020). However, the additional weight due to the onboard battery pack can be compensated by the additional ZEV weight allowance, which is 2.000 kg, from replacing a conventional diesel engine with an zero emission drivetrain, such as battery electric drivetrains. The illustrative calculations below describes this for long-haul heavy-duty battery electric vehicles in both 2020 and 2030.

Table A4: Overview load weight from the literature. Based on (Transport and Environment, 2020)

	Parameter	Formula	Value 2020	Value 2030	Source
A	Energy consumption at the wheels (kWh/km)		1,15		Earl et al. (2018)
B	Nominal range (km)		800		Kühnel et al. (2018)
C	Usable battery capacity (%)		80		Tesla (2021)
D	Required battery pack size (kWh)	$\frac{A * B}{C}$	1.150		
E	Battery pack energy density (kWh/kg)		0,2	0,318	Ricardo (2019), Hall et al. (2019)

F	Battery pack weight (kg)	$\frac{D}{E}$	5.750	3.616	
G	Weight of other electrical components (kg)		600		Hall et al. (2019)
H	Total weight of electric drivetrain (kg)	$F + G$	6.350	4.216	
I	Weight of conventional diesel engine and fluids (kg)		3.000		Sharpe (2019)
J	Net additional weight of electric drivetrain (kg)	$H - I$	3.350	1.216	
K	Maximum additional weight allowance (ZEV) (kg)		2.000		European Union (2019)
L	**Net payload loss electric drivetrain (kg) (up to a minimum of zero)**	$\boldsymbol{J - K}$	**1.350**	**0**	

It is important to note that studies are not consistent when it comes to energy consumption at the wheels (A). Here, is calculated with 1,15 kwh/km. However, Hall states 1,6 kWh/km for and energy consumption at the wheels. Calculating with these numbers would result in a net payload loss of +/- 3.600 kg (L) in 2020. The net payload loss in 2030 is expected to be +/- 630 kg (L), which is in both cases significant. The difference in battery pack energy density (E) can be explained be assumptions of the rate of innovation and timeframe, where Hall (2019) is more conservative and predicted short-term values.

Furthermore, where battery pack weight (F) is expected to be 3.616 kg (Transport and Environment, 2020). Hyzon Motors states a battery pack can weigh between 5-8 metric tons (Hyzon motors, 2021). To conclude, the literature is not consistent and uses a wide range of assumptions. Therefore, it is hard to conclude what load weight losses can be expected from the literature. In a worst case scenario, load weight losses are expected to be several tons (up to 3.600 kg). In a more favourable scenario, load weight losses are close to zero kg compared to diesel. However, it can be assumed that this would be at a high innovation rate and a long time horizon (2030).

An example from practice is the DAF CF as mentioned before. The conventional diesel configuration has a weight of less than 7.000 kg. The electric variant of the same model, which only has a driving range of 220 km, weighs 9.000 kg (DAF, 2021). Applying the ZEV weight allowance, this would result in no load weight losses. However, it should stretched that this truck only has a driving range of 220 km. Comparing this to the literature, there is a significant difference.

Truck power

The calculations followed from the literature are based on 350 kW electrical drivetrains. However, the DAF CF electric only has a power of 210 kW (DAF, 2021), which is a substantial decrease. Commonly used trucks in long-haul transportation often have a power of 300 kW or more, hence the 350 kW in the calculations. However, when hauling heavy cargo, torque is more important than power. Electric vehicles are commonly known for the excellent torque outputs. In heavy-duty trucks, this is no exception. In the table below, an overview is provided of the characteristics of the same model, where one has an electric drivetrain and the other a common diesel drivetrain. To conclude, performance wise, electric trucks do seem to be feasible.

Table A5: Drivetrain characteristics overview (DAF, 2021)

	DAF CF Electric	**DAF CF Diesel**
Power (kW)	210	300
Torque (Nm)	2.000	2.000

Refuelling infrastructure

When "refuelling" an battery electric vehicle, there is spoken of "recharging". Therefore, in this chapter, there will be referred to an recharging infrastructure.

The expansion of electric trucks employment cannot be separated from the supporting charging network. As the typically complementary commodities, the outcome of their mutual influence will determine their further development. Electric trucks', and BEVs in general, potential buyers considering their EVs charging convenience, is a core issue in the recharging infrastructure, especially in the early stage of the battery electric trucks' widespread popularization. This problem often is labelled as the chicken-and-egg dilemma (Shi et al., 2020). Which is similar to the problem regarding the hydrogen refuelling infrastructure.

Looking at the graphs of Oplaadpunten.nl (2021), recharging stations are well represented in the BeNeLux, followed by Germany, Swiss, Austria, France and the UK. Unfortunately eastern European countries, such as Poland, Czech republic, Hungary and Slovakia are lacking behind when it comes to recharging infrastructures. Furthermore, the recharging possibilities in Italy and Spain are close to zero as well.

In the table below, an insight is provided of recharging stations per square kilometre of a grasp of European countries. However, it should be noted that countries might differ in recharging connectors. Furthermore, not all recharging stations are so called "fast chargers".

Table A6: Recharging stations per country. Based on information of ANWB (2021)

Region	Recharging stations	Recharging stations per km^2
Europe	200.000	0,02
Netherlands	58.000	1,40
Belgium	8.000	0,26
Luxembourg	950	0,37
Germany	43.000	0,12
France	44.000	0,07
Austria	7.000	0,08
Italy	13.000	0,04

In the short-term future, charging stations will be sized according to the demands. Fast charging stations will be built on the highway network and logistic service providers will have to cope with relatively low levels of power at their facilities. Future development is likely to start with the sites where sufficient capacity is available (Earl et al., 2018). This capacity will not be sufficient in the future for two reasons, namely: technological progress (Delgado et al., 2017) will likely cause more powerful batteries to be brought to the market and battery electric truck sales will likely increase when there is wider uptake of electric vehicles beyond a niche (Earl et al., 2018).

Opportunity charging occurs when loading and unloading goods or during the driver's rest time. When this opportunity charging strategy is applied, the need for smart management of charging will be essential as infrastructure builders, like FastNed, should look for a trade-off when building fast charging infrastructures. This will include selecting the right number and power ratings of chargers versus the average battery sizes (Earl et al., 2018). From a logistics service providers perspective, the battery size, timetables, dwell times must be optimized to avoid unnecessary costs and time losses. Furthermore, long-haul heavy-duty trucks require, in general, higher power outputs in order to recharge to an sufficient capacity to complete the next segment of their trip (Earl et al., 2018).

Transport time

Refuelling time

Every minute a driver has to stop is a large cost to logistics service provides and will be translated in a higher price per kilometre. Again, taking the DAF CF Electric as an example, a full charge (350 kWh) will take 75 minutes at a 250 kW recharging stations. However, as discussed before, not all chargers are fast chargers. Chargers range up to 300 kW in the Netherlands. However, 50 kW are more common (Fastned, 2021). Besides that, most battery packs are not able to charge with 300 kW rate. For example, the Scania BEV, which is a rigid truck, can only charge with a rate up to 130 kW (Scania, 2021).

Driving range

As discussed before, driving range is included in two trade-offs between load weights and truck performance, assuming constant energy density. An increase in driving range will cause an increased battery pack weight and therefore a reduced load weight. This is the trade-off mentioned by Ben van Beurden.

Tesla claims that their battery electric truck, can have a driving range up to 800 km. This is a significant increase compared to other battery electric trucks, especially when only considering tractor configurations. Again, the DAF CF Electric, which has a claimed range of 220 km, has a reduced driving range of approximately 93% compared to similar diesel trucks. This means that, when driving at an average speed of 90 km/h, every 145 minutes (2,4 hours), the driver needs to recharge for at least 75 minutes. Although drivers need to rest every 4,5 hours for 45 minutes (Rijksoverheid, 2021B), it is considered a large burden. Especially when recharging infrastructure is limited or when recharging stations only have low power outputs. What would mean detours or longer recharging times.

Looking beyond the scope of tractor configurations, the rigid configuration of the Volvo FL Electric claims a driving range of 300 km with a battery capacity of 300 kWh. Which is 50 kWh less than the DAF CF Electric. However, as the Volvo has a rigid configuration, maximum load weights are limited. Hence, the relative increase in efficiency.

Energy availability

The total energy demand of a fleet of battery electric trucks in the EU is an important metric for anticipating generation requirements (Earl et al., 2018). This will mainly depend on charging strategies that are implemented by logistic service provider. For comparison, the average annual electricity consumption of a household in the EU is 3,5 MWh , implying a single truck charge of 1 MWh, which is a future assumption, would be around 1/3 of the annual consumption of an average household (Stewart & Dodson, 2016). In terms of power, assuming future fast charging with a 1 MW charger, a battery electric truck would draw as much power as 2500 houses (Earl et al., 2018). This can be confirmed by an article from the Financial Times that stated that a long-haul heavy-duty electric truck requires an amount of energy similar to the electricity consumption of 3.000 to 4.000 average UK houses per truck charge (Józwicka, 2016).

Implementing full fleets of battery electric vehicles on the road, the question arises whether or not the energy grid and generated capacity in Europe is sufficient regarding the added demand. To get an order of magnitude, the total electricity required to charge a European fleet of long-haul heavy-duty trucks would be equal to 324 TWh. This is over 10% of EU generation in 2015, what was 3.000 TWh. (Earl et al., 2018)

A possible new BEV load, in the form of electric trucks, that could be added to power grid is notable in energy demand. Because, it is not only having a significant energy demand but also an unpredictable dynamic behavior. Moreover, when and where these vehicles are going to be connected for charging, duration of charging, amount of real and reactive power going to be drawn from the electrical grid by them is hard to assess in advance (Dharmakeerthi et al., 2011). A number of supply and demand studies can be found in the literature and these studies tested and evaluated different electrical grids around the world. These studies all came to similar conclusions where they state that an increase in BEVs brings a large degree of temporal and spatial diversity to the energy grid (Dharmakeerthi et al., 2011).

However, considerable numbers of battery electric trucks brings, besides the challenges, opportunities for the electric energy grid as well. This depends on the control strategy (Faddel et al., 2018). On one hand, they can cause negative impacts on the grid, as explained earlier. These impacts can range from line overloading in both primary and secondary distribution systems to transformers overloading (Ghavami et al., 2016; Masoum et al., 2012), line losses (Sortomme et al., 2011), low voltages and voltage fluctuations (Richardson et al., 2010). On the other hand, BEVs, as controllable loads, can provide more flexibility to the system operator in demand side management, flattening out the demand curve by better valley filling and peak shaving and increasing the system efficiency, a so called "smart grid" (de Creamer et al., 2014). Furthermore, they can provide ancillary services to the grid, such as regulation and reserve services (Sarker et al., 2016). This is especially important for power systems in the presence of high share of intermittent renewable energy resources where the system inertia is a big challenge (Faddel et al., 2018). Considerable group of battery electric trucks can help mitigate the inertial loss by behaving as a large storage unit (Zhang et al., 2017). BEVs in general, can be valuable for local voltage and reactive power support as well (Mojdehi & Ghosh, 2016)

Assessing the literature found above, BEV can have positive impact on electrical grids. However, it is hard to predict whether or not the energy supply can meet the demand of the increased numbers of battery electric trucks when implemented at a large scale.

Biodiesel HVO

Truck performance

Load length and weight

HVO can be used in most conventional diesel trucks without any mechanical modifications to the truck. Therefore, both load length and load weight are not affected by the implementation of this alternative fuel. This means the threshold for the adoption of this fuel is fairly low.

Truck power

If HVO is blended with EN 590 diesel fuel, the blend meets EN 590 specification until the lower limits of an volumetric density of minimum 820 kg/m3 in the summer and 800 kg/m3 during the winter is met. This limit is often present at a mix rate of about 30% of HVO and 70% of diesel fuel (Kuronen & Mikkonen, 2007). In other words, up to HVO30, the blend meets EN 590 specifications.

The energy content of alternative fuels is important measure to assess power deliveries to the wheels. Energy content of HVO is approximately 34.4 MJ/liter, diesel has an energy continent 35,7 MJ/liter, which is slightly more. Therefore, the fuel injection system may need recalibration in order to get full torque and power output due to the lower fuel density of HVO (Kuronen & Mikkonen, 2007).

Furthermore, a research, done by Sugiyama et al. in 2011, states that the volumetric heating value of HVO is 5% lower than diesel, creating the concern that torque might decrease at full load. It was found that the same torque and the same brake specific energy consumption could be obtained with HVO even at the same indicated value of injection duration as diesel fuel (Sugiyama et al., 2011). This is due to an increased injection quantity of HVO and similar heating values are obtained. The results show that, despite its lower volumetric heating value, HVO does not result in lower torque in full load operation (Sugiyama et al., 2011). Moreover, as a result of an optimized engine calcification, HVO is capable of improving partial fuel consumption and full-load torque. These results indicate that HVO has beneficial fuel characteristics when applied to diesel engines (Sugiyama et al., 2011).

To conclude, performance wise, an HVO powered truck has similar characteristics as an diesel configuration.

Refuelling infrastructure

In 2019, 14.449 diesel refueling stations were registered in Germany and over 105.000 in Europe (Peters et al., 2021). This implies that the infrastructure for liquid fuels in Europe is proven and sufficient. However, the possibility of conversion to liquid alternative fuels have to be considered to ensure, that fuels can be provided in the existing infrastructure. Peters et al. (2021) states that the conversion from diesel to bio-diesel is fairly easy and without any large costs. Therefore, the difficulty of implementing an HVO based infrastructure is considered to be easy.

According to the website of NESTE (2021), there are currently more than 100 HVO refuelling stations in the Netherlands. This means there is an existing supply chain present. Following from the statements that conversion is easy, scalability of this HVO infrastructure is considered to be sufficient when the rate of demand increases.

Transport time

Refuelling time

Due to the similarities with diesel, refuelling times are equal to diesel.

Driving range

As stated by Kuronen & Mikkonen (2007), the heating value of HVO is higher than that of conventional diesel fuel. Therefore, mass based fuel consumption will usually be lower for HVO. They state, the mass based fuel consumption was 1,2-1,9 % lower with HVO100 compared to regular diesel. This is confirmed by CO2 measurements at the tailpipe. However, the volumetric fuel consumption was 5-6% higher with HVO due to a difference in densities (Kuronen & Mikkonen, 2007). Furthermore volumetric fuel consumption of HVO50 increased by 2%. As a summary, because of a lower density volumetric fuel consumption is slightly higher when engines are driven on HVO rather than conventional diesel. When 10-30 % HVO is mixed with diesel the difference in volumetric fuel consumption are very low (Kuronen & Mikkonen, 2007). This means that, due to higher volumetric fuel consumption, driving range decreases accordingly. In other words, the driving range is estimated to be equal to diesel or up to 5.8% less with regard to equal tank sizes, depending on mix ratio.

Energy availability

One of only a few stand-alone HVO manufactures is a Finnish company called NESTE Oil. With facilities in Singapore, Finland and in the Netherlands bring their production capacity up to 2 million ton of HVO per year. Furthermore, future co-refineries are expected (Biokraftstoffe.fnr, 2016). Future availability of this fuel is hard to predict. As this product is bio-based, it depends on natural sources, what could be become a problem in the long-term. Again, to what extend is hard to predict.

LNG

Truck performance

Load length

The volumetric efficiency of LNG is 1,7 times lower than diesel. In other words, 1 liter of diesel will be replaced by 1,7 liters of LNG when other parameters do not change (Smajla et al., 2019)

Load weight

Volvo, states equal payload performances with regard to diesel (Volvo, 2021).

Truck power

LNG powered trucks can be regularly seen on the road. In other words, there are real world applications of this type of propulsion. IVECO offers a LNG powered truck with 460 HP and 2.000 Nm (IVECO, 2021), which is similar to diesel configurations. Furthermore, Volvo offers two different LNG configurations of their Volvo FM, one with 420 HP and one with 460 HP (Volvo, 2021). Again this is similar to common diesel trucks.

Refuelling infrastructure

As mentioned before, using natural gas in heavy-duty applications is already in use in different parts of the world (Peters et al., 2021). Heckler et al. (2020) stated current and planned LNG stations in Germany. 30 LNG refuelling stations are already operational and an additional 46 are about to be build. Furthermore, they announced a target for the German administrations to build 50 refuelling stations for 2.500 LNG trucks before 2020 and 200 refuelling stations for 25.000 trucks by 2025. If the 2020 objective has been met, became clear after consulting the website NGVA.EU (NGVA, 2021). Currently, there are 57 LNG refuelling stations operational in Germany. The Netherlands accounts for 28 stations and Belgium for 18. Furthermore, Poland has 5 refuelling stations and the UK has 15 stations operational. In total, Europe counts approximately 390 LNG refuelling stations.

Transport time

Refuelling time

Refuelling times are equal to diesel (Volvo, 2021).

Driving range

For liquefied gases such as LNG only requires changes in the storage system of the fuel. As stated by Peters et al. 2021: “With LNG, a range of 1693 km is achievable”, assuming a 557 kg tank capacity. However this resulted in a loss of load weight of around 500 kg (Peters et al., 2021). Smajla et al. (2019) states a fuel cycle of 950-1200 km between refueling stations.

Iveco Stralis Natural Power mounts two LNG tanks between the first and second axle that can achieve a driving range of 1.600 km (IVECO, 2021). However, IVECO builds a low-deck configuration, as used in the automotive industry, as well. This low-deck tractor has a maximum range of up to 1.150 km (IVECO, 2021). Although the decrease this is still sufficient for modern day long-haul transportation. Furthermore, Volvo build LNG powered trucks as well. They claim a driving range of up to 1.000 km (Volvo, 2021). This is comparable to IVECO's statements. No load weight losses are mentioned In the specification sheets of both manufacturers.

Energy availability

LNG has already been applied in maritime traffic, and in Norway it is also considered to be used in railway transport (Smajla et al., 2019). In other words, LNG is already included in existing industries. However, LNG is a fossil fuel and is therefore finite (Yavuz et al., 2015).

Economical perspective

Hydrogen

Purchase costs and depreciation

It seems that investment costs are a large obstacle for logistic service providers when it comes to hydrogen powered trucks. This is because hydrogen trucks require twice as much investments as comparable diesel trucks. In the table below an overview is provided of current and future CAPEX.

Table A7: CAPEX values hydrogen truck in euro. * grey literature

	Current CAPEX	Future CAPEX	Year
(Oostdam, 2019)	442.000	257.000 - 335.000	-
(Moultak et al., 2017)	300.000	207.000	2030
Hunter & Penev, 2019)	492.000	184.000	2040
(Vijayagopal & Rousseau, 2019)	316.000	175.000	2050
(Hyzon motors, 2021) *	285.000	178.000	-
(Cleantechnica, 2021) *	321.000	-	-

The table above shows a wide spread of values. On order to provide usable results, the average current CAPEX will be calculated, which is an average of 359.000 euro. Assuming a residual value of 50.000 euro over a 6 year period (Oostdam, 2019) and an average annual driving distance of 125.000 km, this would results in an euro/km of 0,41.

HYZON motors claims a lifespan, in driving distance, of 700.000 miles, which is +/- 1.125.000 km (Hyzon motors, 2021). This would result in 0,27 euro/km. Which is a significant difference when driving long distances.

Tax and incentives

As hydrogen trucks do not emit green-house gasses in an Tank-To-Wheel analysis, they are exempted from future CO_2 tax. Furthermore, as of February 2021 the Dutch government announced new subsidy regulations for Zero Emission Vehicles above a curb weight of 4.250 kg (Rijksoverheid, 2021A). These regulations involve a financial incentive to test ZEV in practise. For this incentive the Dutch government allocates 11 million euro for companies to get started with these test. How this exactly relates to individual companies or truck is hard to determine. Especially, when converted to an euro/km.

Current and future fuel costs

Fuel costs strongly depend on the market size and respective fuel demand, because a significant share of the fuel cost is made up of capital expenditures for production and storage facilities, meaning the hydrogen logistics and the refueling station itself (Peters, et al., 2021).

The size of a refuelling station strongly influences the price of hydrogen, because of economy of scale effects. As the hydrogen price is currently fixed to 10 euro per kg and there are only a few examples of fully utilized hydrogen refuelling stations, it is difficult to determine the refuelling cost for the future (Oostdam, 2019). Oostdam states that the price of the refuelling station is expected to decrease as the utilization and capacity of a HRS increases. He states that it is estimated that the price could decrease to 1,00 euro per kg or less. According to Weeda (2019), it can approach 0,50 euro per kg if fully utilized and 1,00 euro per kg using a more conservative prediction. This is similar to a report from the Fuel Cell and Hydrogen Joint Undertaking (FCH JU), which mentions prices less than 1 euro (McKinsey, 2010). Converting this to a cost per km, using an energy consumption of 13 km/kg, it would results in 0,77 euro/km when currently implemented. However, fuel costs might trend towards 0,08 euro/km or lower.

Maintenance costs

Maintenance costs are hard to predict as no hydrogen trucks are commercially available yet. Nevertheless, as there are fewer parts in hydrogen truck, it is expected that maintenance intervals will be lower. However, as it is a new innovation, mechanics might need to be educated to do maintenance on these vehicles. This might lead to increased costs. The assumption will be made that the maintenance costs of a hydrogen powered truck will be similar to a diesel truck on a yearly basis. However, to provide an insight, Hyzon Motors claims that maintenance on their hydrogen trucks will cost 0,11 euro/km (Hyzon motors, 2021).

Fuel price stability

Blue hydrogen prices depends on natural gas prices. Green hydrogen depends on electricity prices. This makes the volatility of hydrogen directly related to either electricity or gas prices (Mulder, Perey, & Moraga, Outlook for a Dutch hydrogen market, 2019). Natural gas includes winter effects. In other words, gas prices rise during the winter. In the last 20 years the average volatility trends upwards. Currently it is around 20% (Alterman S. , Natural gas price volatility in the UK and North America, 2012).

Battery electric

Purchase costs and depreciation

The conditions for battery electric trucks (BETs) have drastically changed since 2010,. In that year, lithium-ion battery prices were around 900-1.200 euro per kWh (Wolfram & Lutsey, 2016) including an energy densities of approximately 110 Wh/kg . In 2018, prices decreased with a factor of around four, and energy densities have at least doubled. In other words, batteries are cheap and dense enough to be considered as viable for powering trucks (Earl et al., 2018). These trends in reduced costs and improvement in energy density has led to, and been driven by as well, a rapid increase in passenger electric vehicles, electric urban buses, and the emergence of heavy duty trucks (Earl et al., 2018).

Following from a study done by Earl et al. in 2018, he stated the following: Before analysing the total CAPEX, it is worth mentioning the underlying battery price. Indeed, a large uncertainty when analysing the economic feasibility of battery electric trucks is the price per kWh of the battery. Allocating the entire purchase cost of the Tesla Semi to cover only the cost for the estimated 1.000 kW large battery, would suggest a battery cost of 150 euro/kWh. This can be confirmed by cost predictions made by (Wolfram & Lutsey, 2016; Moultak, Lutsey, & Hall, 2017). It should be noted, that this price is a gross overestimate, ignoring the cost of the other components of the truck and profit margins. Alternatively, the price difference between the two models can be considered, assuming that the price difference is attributable only to the battery size. Comparing the 475 km model to the 800 km model, there is a price difference of approximately 25.000 euro. This would result in a battery price around 70 euro/kWh. Which is a price that approaches optimistic 2030 battery price expectations. The actual price is probably somewhere within this range of findings, and is estimated to be around 100 euro/kWh (Earl et al., 2018).

Tesla's battery electric truck with a 800 km range will set logistic service providers back around 150.000 euro (Cleantechnica, 2021). However, it is likely this excludes optional extras desirable for EU customers. For comparison, the best in class truck in the EU with similar add-ons would around 110.000 euro. A Logistic service provider, seeking to buy a new truck for long-haul transportation would likely use the truck as much as possible, so an annual driving distance of 125.000 km is assumed. Furthermore, assuming a residual value of 50.000 over a 5 year period would result in around 0,16 euro/km.

Tax and incentives

Tax and incentives are announced by the Dutch government (Rijksoverheid, 2021A). However, for whom and for what applications isn't clear yet. This is similar to the situation hydrogen is in.

Current and future fuel costs

Fuel costs are sensitive parameter in the cost calculations. On the one hand, the current diesel cost of 1 euro/litre (Calvo Ambel, 2015) applicable to logistic service providers is known with high certainty. Unfortunately, the electricity cost that will eventually be charged for recharging electric trucks is more uncertain. Today, the EU average industry rate is 0,12 euro/kWh whereas Tesla superchargers for cars are currently 0,24 euro/kWh (Earl et al., 2018). This should be put in the context of the Shell supercharger charging 0,55 euro/kWh and Tesla promising 0,06 euro/kWh (Earl et al., 2018), what implies a wide range of prices. When assessing these costs, the EU industry average with the option of supercharging should be considered. As can be seen, the cost of electricity will determine the cost competitiveness of battery electric trucks in the EU (Earl, et al., 2018).

Maintenance costs

For conventional diesel trucks maintenance is quite extensive since they have many moving parts and usage causes a lot of wear. Fortunately, battery electric trucks require less maintenance and repairs compared to conventional diesel vehicles (Huismans, 2018). According to (Onat et al., 2015), maintenance costs for an BEV is approximately 65–80% of that of an equivalent diesel engine due to fewer components and moving parts, as well as lower maintenance requirements for electric motors.

Maintenance of electric vehicles includes the possibility of replacing the battery after its life-time as well. Other component on trucks, such as chassis and motors, tend to have longer life-cycles, this fact is often overlooked but should be accounted for as well (Huismans, 2018).

Considering maintenance and repair costs from the impact assessment (Maibach & Sutter, 2006) from the European Commission. They equate to 12.500 euro per year for internal combustions engines, such as diesel engines. It is estimated that battery electric trucks account for half of that, due to the much simpler drivetrain as described before. This is in-line with BEUC (Stewart & Dodson, 2016) findings, who use this reduction as well. However, they mention that there is a large variation of reported maintenance costs. Furthermore, the EEA report, Electric vehicles in Europe (Józwicka, 2016), claims ‘significantly less maintenance costs’. Research, done by Earl et al. (2018), shows maintenance costs of 0,10 euro/km.

Fuel price stability

The price of electricity at the recharging station is inevitable linked with the price of electricity in general. The average price volatility of electricity in the UK is estimated to be around 40% (Ofgem, 2021)

Biodiesel HVO

Purchase costs and depreciation

As common diesel engines are used in the case of HVO, similar values are found. In other words, a purchase cost of 100.00 euro and a residual value of 40.000 euro is assumed.

Tax and incentives

There is no information available about possible grants or incentives for HVO powered vehicles.

Current and future fuel costs

Information regarding this fuel is limited. Therefore, sources are not able to confirm or deny each other. Current fuel costs were found of 1,47 euro per litre (DCB Energy, 2021). unfortunately, future fuel costs predictions are unknown and highly uncertain.

Maintenance costs

Regarding maintenance costs, similar statement can be made as the purchase costs. Due to the similarities with diesel, maintenance costs are expected to be 15.000 euro per year.

LNG

Purchase costs and depreciation

Westport Fuel Systems (2021), state an additional CAPEX of 40,000 euro for an LNG vehicle with HPDI technology compared to diesel configurations. The incremental price as stated by Westport is confirmed by the 35.000 to 50.000 euro estimations in Germany done by Anderhofstadt and Spinler (2019). Furthermore, a 2013 research shows an incremental price for LNG trucks of 30% to 40%. Assuming a CAPEX for diesel of 100.000 euro, this is inline Westport’s statements.

Tax and incentives

In 2019, the Dutch government announced an incentive for LNG, they announced that for the years 2020 and 2021, transport companies receive 0,187 euro per kilogram of LNG. This is directly compensated at the refueling station (Volvo, 2021).

Furthermore, in Germany, there is an incentive as well. This so called “MAUT-exemption” determines that LNG powered trucks are not obligated to pay MAUT, which is a German tax. Depending on truck-trailer combination weight, this can result in fuel price savings up to 0,187 euro per kilometer (Volvo, 2021).

However, Peters et al. (2021) state that if the energy tax reduction for natural gas does not apply in the future and the same tax as diesel applies to LNG. Moreover, if LNG is taxed relative to diesel on a carbon basis, no possibilities for financial savings are possible by switching to LNG (Peters et al., 2021).

Current and future fuel costs

A study concerning, fuel cost savings per year when converted to LNG, made the following assumptions: line haul use in the U.S. at 160.000 km per year, an overall fuel consumption of 2,55 km/L using diesel as an reference, and a diesel price of 0,94 euro per liter. The cost of LNG was assumed to be 0.59 euro per liter per diesel equivalent. Assuming these figures, they concluded a fuel cost saving of between 19.029 and 13.863 euro per year when a LNG drivetrain is used (Americas Commercial Transportation Research, 2012). Similar findings have been done by Smajla et al. in 2019. On average, they state a reduction in fuel of LNG powered truck of around 48% less than for diesel trucks. According to these cost expectations, the payback period is less than three years (Smajla et al., 2019).

They assumed 120,000 km as an annual mileage and 1,36 euro per L for diesel and 0,95 euro per kg for LNG. Assuming a consumption of 3,3 km/L for diesel fuel and 4,8 km/kg for LNG, they concluded a payback period of 19 months and annual fuel cost savings of around 25.100 euro per year with natural gas. Similarly, Smajla et al. (2019) concluded that, for a driven distance of 124.000 km per year, a LNG powered truck produces a cost saving of 14.500 euro, assuming a diesel price of 1,5 euro/L and an LNG price of 1,33 euro/kg (Peters, 2021).

Maintenance costs

Smajla et al. (2019) states that a LNG trucks is around 20% more expensive than similar diesel configurations. This is estimated to be around 11.500 euro and 9.500 euro respectively.

Diesel reference

Table A8: Diesel reference

Diesel references	costs per kilometre	Remarks
Purchase-depreciation	0,13 euro	Purchase: 100.000, residual: 40.000 euro
Fuel cost	0,32 euro	
Maintenance cost	0,12 euro	15.000 euro per year
Fuel price stability	100% volatility	(Zlatcu et al., 2015)
total	0,52 euro	

Based on 125.000 kilometre yearly mileage and a 6 year lifespan.

Appendix B: Route details

Route 1

Route description

Route 1 involves cluster 1. This cluster is located in Great-Britain and houses six suppliers which are located only 50 km from each other and are responsible for around 31 trips per week in total. This route starts at Southam and uses the train between Dover and Calais. Afterwards the trip continues to Born when in total around 640 km are driven.

Route score overview

Table B1: Route 1 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	8,5	0
BEV	10	6,8	7,3
HVO	1,4	10	9,3
LNG	1,9	8,5	9,2

Hydrogen scores

As explained before, when discussing hydrogen powered vehicles, a 100% reduction of TTW emissions is realized.

When starting the trip in Southam and using the shortest path, the truck comes across three hydrogen refuelling stations, from which one is currently in development. Assuming 500 km range, as explained before, and a trip distance of 640 km, there is a sufficient amount of refuelling possibilities in this scenario. However, due to the geographical location of the second and third refuelling station, the first one, located near London, is a required refuelling point in order to make the trip feasible. In other words, refuelling infrastructure wise, no additional time, caused by detours, is expected. Furthermore, refuelling time should be evaluated. Due to the fact they only need to be refuelled once, 5 extra minutes should be taken into account. However, 5 additional minutes on a 640 km trip is neglectable with regard to traffic or potential traffic jams. Furthermore it is important to note that truck fuelled by flammable gasses are not allowed in the tunnel (Eurotunnelfreight, 2021). This implies the use of the ferry which causes an transport time increase of around 15%.

At last, cost should be considered. Due to the technological feasibility of the shortest route, as used by diesel applications, no additional kilometres are driven. Therefore, making the cost per kilometre, as stated in the literature findings, relevant for this case. This is a 127% increase relative to commonly used diesel configurations.

Battery electric scores

the infrastructure coverage of recharging station in Great Britain, Belgium and the Netherlands is sufficient for battery electric vehicles. However, an 60 km long stint in France has no recharging infrastructure on this section of the route. This should be taken into account when planning the trip. Due to the limit range, it is required to recharge at least two times. This adds approximately 200 minutes to trip. However, it could be argued that recharging time could be combined with obligated breaks. therefore, the additional time is expected to be 155 minutes, which results in at least 32% increase of transport time.

As explained before, LSPs use price per kilometre as a business model. However, when BEV are implemented to could shift towards a price per time unit, due to the additional transport time. Therefore, transport costs are expected to increase. The total costs of BEV on this route are expected to increase with a minimum of 27%.

HVO scores

HVO is currently only publicly available in the Netherlands with regard to the countries that this route runs through. However, there are companies who supply HVO upon request in those countries. This makes implementation hard at first. However, converting regular diesel pumps to suit HVO requirements can be done without large costs, therefore making scalability easy. Due to mix ratios with regular diesel, the trip is considered to be feasible. However, assuming a truck would tank HVO100 in the Netherlands and drives to the supplier, the kilometres driven on HVO on the way to born would only be 300 kilometres, which is around 47% of the trip. Therefore, the maximum potential of reducing green-house gasses is not reached. Nevertheless, HVO has no effect on transport time. The score in this evaluation are based on 300 km driven on HVO and 340 km on regular diesel.

LNG scores

Combining the large driving range and an extensive LNG refuelling structure, no additional emissions, and costs, caused by detours, are expected. However, due to safety restrictions gas LNG powered vehicles are not allowed to take the tunnel. Therefore it is required to make use of the ferry. This causes an increase in transport time of over 15%.

Route 2

Route description

Cluster 2 is evaluated in this section. This cluster originates from south-east Germany (Regensburg) at an distance of 610 km relative to Born. Here, two large suppliers are located within a distance of 80 km of each other. These suppliers sum to a total of 19 Full-Trailer-Loads per week.

Route score overview

Table B2: Route 2 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	10	0
BEV	10	6,6	7,2
HVO	1,6	10	9,2
LNG	1,9	10	9,2

Hydrogen scores

When driving the shortest path, the truck comes across HRS in Neurenberg, Würzburg, Frankfurt, Bonn, Cologne and Aachen with a maximum distance of 175 between HRS. making this route with this fuel feasible as well, without any detours. However, from a practicality point of view, it should be noted that there are no HRS available near Born, what could be an inconvenience when travelling in the other direction. Assuming only one refuelling moment on the trip, the additional 5 minutes in refuelling time are neglectable when considering traffic on route of over 610 km.

Furthermore, due to the fact that no detours are required to make the trip feasible, no additional cost on top of the predetermined costs are expected.

Battery electric scores

the recharging infrastructure in the Netherlands and Germany is well thought out and is sufficient for BEV to be able to drive the shortest route without detours. However, on this 610 kilometre long trip, it is required to recharge at least two times. Subtracting the obligated breaks, would results in an additional transport time of 155 minutes, which is a 34% increase. This increase in time and the potential new business model would result in additional costs as well. These are expected to increase with 28%.

HVO scores

As explained earlier, HVO is only publicly available in the Netherlands. Therefore, on this 610 kilometre long trip, only 330 kilometres can be driven on HVO in the current situation. Therefore, emissions are not optimized. However, costs are slightly lower when compared to 100% implementation. Again, transport times are not affected by implementing HVO powered trucks.

LNG scores

Germany has a well build LNG infrastructure. Therefore, no implications of the initial findings are caused by assessing the scores of this route.

Route 3

Route description

In the area of Dobrany in the Czech Republic two suppliers are located at a distance of 30 kilometres to each other. This route from cluster 3 to Born is approximately 715 kilometres from the cluster centre and involves a weekly transported volume of around 340 m^3.

Route score overview

Table B3: Route 3 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	10	0
BEV	10	5,2	6,2
HVO	0,1	10	9,5
LNG	1,9	10	9,2

Hydrogen scores

The distance between the cluster centre and the nearest HRS is around 210 km, meaning that the truck needs to have at least a 50% fill level when leaving the supplier to make to trip feasible without any risk. However, 100% fill levels are assumed when leaving the suppliers. After the first HRS has been passed, the trip follows the exact same route as described in route 2. This makes route 3, using hydrogen, technological feasible as well, as long the truck has at least a 50% fill level when leaving the supplier. To conclude, this route does not involve detours and no additional costs are expected.

Battery electric scores

The Czech republic has almost no recharging stations operational. Fortunately, Dobrany is located near the border of Germany making this route using BEV feasible. However, due to lack of infrastructure in the area of Dobrany, trucks leave the supplier with only a 50% battery percentages. Therefore, it is required to recharge at least three times during this trip. This results in an additional transport time of at least 255 minutes when breaks are subtracted. This implies an transport time increase of 48% and additional costs of 38%.

HVO scores

Similar findings are obtained when assessing this route as to other routes using HVO. Due to the current lack of infrastructure in European countries, only a percentage of the entire route can be driven on HVO. Therefore, only 225 kilometre can be driven on HVO. This is less than 32% of the trip.

LNG scores

As explained before, the LNG infrastructure is highly sufficient in western Europe. Therefore, this route does not affect the scores regarding LNG powered trucks.

Route 4

Route description

Cluster 4, and therefore route 4, is a cluster spread across three countries. These are Poland, the Czech republic and Germany. Near these national borders four suppliers are located which are responsible for almost 6.500 m^3 per week. This more than 30% of total weekly transported volume within the JIT/JIS supply chain strategy of VDL Nedcar. The centre of the cluster is located near Piensk (Poland) at a distance of roughly 770 km relative to Born.

Route score overview

Table B4: Route 4 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	8,9	0
BEV	10	8	8,2
HVO	0,1	10	9,7
LNG	1,9	10	9,2

Hydrogen scores

The nearest HRS relative to Piensk is located near Dresden, Which is located near the shortest route to Born, at a distance of 122 km. However, this HRS is located near the city centre and therefore inefficient and hard to reach by full sized heavy-duty trucks. The same applies to a HRS near Halle. However, there is a suitable HRS located near Kassel at a distance of 460 km to Piensk, meaning some risk is involved. An alternative is to drive in the direction of Berlin where in Potsdam a HRS is operational. This detour would add around 85 kilometres to the trip which is an 11% increase. However, this involves lower risks as there are over 15 HRS operational on this route. This detour would imply around a 152% increase in total route costs.

Another option is to drive in the direction of Meerane but this implies a minimum fill level at the supplier of 50% to make it feasible. This route will increase the trip distance with 3% and involves less risk as well. Due to these detours transport time and total route cost will increase.

Battery electric scores

Poland counts only 14 recharging stations for BEV in their country. Luckily, Piensk is located near the border of Germany, with the nearest recharging station just a couple of kilometres away. The fact that the driver is obligated to take two breaks, benefits the relative recharging time losses. The truck needs to recharge twice, which could be combined with the breaks. The additional transport time is expected to increase with only 110 minutes on this trip, resulting in an increase of only 20%. Additional costs on this route are expected to be around 18%. This is a significant difference compared to previous routes.

HVO scores

Again, due to existing infrastructure and geographical location, only 22% of the trip can be HVO powered. Fortunately, this reduces route costs and doesn’t effect transport times.

LNG scores

Similar statements can be made with regard to other LNG route assessments. No additional emissions, transport time and costs, other than the initial findings, are expected regarding this route.

Route 5

Route description

Route 5 involves an individual supplier which is located in the area near Morsbach in Germany at a travelling distance of 180 km. This individual supplier is responsible for a transported volume of more than 2.600 m^3 per week. This translates to almost 33 trips per week.

Route score overview

Table B5: Route 5 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	10	0
BEV	10	10	9,6
HVO	3	10	8,5
LNG	1,9	10	9,2

Hydrogen scores

As the travelling distance is only 180 kilometres, there no obstacles to make this trip feasible when driving on hydrogen. Especially when considering the large amount of HRS in the area of Düsseldorf and Cologne. Therefore, no extra time and additional costs are expected.

Battery electric scores

Assuming a full battery at the start of the trip, a battery electric truck is able to do drive this route on a single charge. Therefore, no additional transport time is expected, making this route highly suitable for BEV. The increased cost per kilometre is expected to be 0,02 euro. Other than the increased cost per kilometre, no additional costs are expected.

HVO scores

Due to the relatively short route, it is possible to drive fully on HVO, reaching its maximum Tank-To-Wheel reduction potential. However, implementing this fuel has a significant impact on route costs. These costs are expected to increase with more than 15% compared to regular diesel.

LNG scores

Assessing route 5, the implementation of LNG powered trucks doesn't affect the scores. Therefore, the initial findings are solely influential to the scores.

Route 6

Route description

Luneburg is a city located near Hamburg. In this area, a supplier is located that sends only one Full-Trailer-Loads per week. Which is significant less than other routes. However, this route is taken in to account because of the geographical differentiation of the supplier relative to the other routes. This route describes the possibilities when (future) suppliers are located in northern Germany and can contribute towards a more generalizable result.

Route score overview

Table B6: Route 6 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	10	0
BEV	10	8,5	8,5
HVO	3	10	8,5
LNG	1,9	10	9,2

Hydrogen scores

The distance between Born and Luneburg is 475 km, making it technological feasible with one tank. However, that involves some risks. These risks can be countered by the fact that on the shortest route every +/- 100 km there is a HRS operational. Therefore, no detours are required and no additional time and costs are expected.

Battery electric scores

As stated before, the recharging infrastructure for BEVs is well build in Germany. Therefore, no detours are required to make the trip feasible. Nevertheless, transport time will increase due to requirement of single recharging moment. Combining this with the obligated break, approximately 55 minutes are expected to be lost. This results in an 15% increase in transport time and 15% in costs

HVO scores

Due to the 940 kilometre single tank truck range, this trip leaves the truck 10 kilometre short if its destination. Fortunately, there is a refuelling possibility near Venlo, which is located on route. Therefore, the complete trip can be driven on HVO without any additional transport time. However, this 100% implementation increases costs significantly.

LNG scores

The northern part of Germany as a sufficient infrastructure as well. Therefore, no implications are expected.

Route 7

Route description

The next routes originates from France where near the city of Prémont a single supplier is located. Currently, from this area a mere 400 m^3 per week is transported. This translates to five Full-Trailer-Loads per week. Therefore, this route is used to ensure generalizability and takes into account potential future scenarios when new customer(s) bring new suppliers rather than as a large contributor to the current situation.

Route score overview

Table B7: Route 7 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	10	0
BEV	10	10	9,6
HVO	3	10	8,5
LNG	1,9	10	9,2

Hydrogen scores

Due to the fact that the travelling distance is around 250 km between Prémont and Born, a truck could suffice on a single tank. Moreover, there are two possibilities for refuelling on this trip, from which one HRS, near Liege, is still in development. However, these trips would result in a detour of around 110 km (Brussels) or 15 km (Liege). Assuming a single tank trip, no time loses or additional costs are expected.

Battery electric scores

Currently, the recharging infrastructure of France is lacking behind with regard to other western European countries. Nevertheless, this trip is feasible using battery electric trucks due to the close proximity to the Belgium border. In theory the trip would suffice with one battery charge. Although, it is unlikely the truck would be able to begin the trip with a full charge. However, for the purpose of this evaluation, it is assumed that in the near future the infrastructure coverage will increase.

A truck on this route would be able to drive on a single charge. Therefore, no time is assumed to be lost due to recharging thus no additional costs are expected as well.

HVO scores

This route can be fully powered by HVO as the route length is limited to 250 kilometres. By doing so, the Tank-To-Wheel reduction potential is maximized. However, that causes a cost increase of over 15%.

LNG scores

The LNG infrastructure in France is arguably less sufficient for implementing LNG powered trucks. However, due to the close proximity to the Belgium border of this cluster, no implications are expected when assessing this route.

Route 8

Route description

The trip between a supplier located near Holtum and VDL Nedcar in Born is only 3 km, but involves a weekly transported volume of more than 1,100 m^3, which is significant. Furthermore, this trips provides an insight in the possibilities when suppliers are located near plants in a JIT/JIS supply chain strategy.

Route score overview

Table B8: Route 8 scores

Nominal scores	TTW emissions	Transport time	Route cost
FCEV	10	10	0
BEV	10	10	9,6
HVO	3	10	8,5
LNG	1,9	10	9,2

Hydrogen scores

Route 8 involves a travelling distance of only 3 km, meaning that the trip can be made numerous times on one tank. However, the nearest HRS is located near Aachen. What could be considered an inconvenience by the logistic service providers. Nevertheless, no additional time or costs are associated with this route.

Battery electric scores

Due to close proximity of the supplier, battery electric trucks are extremely suitable for these trips. A single truck could accomplish this trip a hundred times on a single charge in the most extreme situation. Besides that, there are a couple of "slow" chargers in the area for overnight recharging and a fast charger is just a couple of kilometres away, making it highly feasible to transport large amount of volume over this route.

HVO scores

Similar conclusion can be drawn from the evaluation of this route regarding HVO. Here, (i) Tank-To-Wheel emissions are optimized, (ii) transport times are not affected and (ii) route costs increase with 15%.

LNG scores

Due to geographical characteristics of this route, a LNG powered truck can be implemented without any compromises. However it should be mentioned that currently, the nearest LNG refuelling station is located near Liege. In other words, if a LSP choses to designate a truck to only this route, refuelling might be inconvenient. However, this is not expected nor advised.