ERASMUS UNIVERSITY ROTTERDAM

Erasmus School of Economics

Master thesis Urban, Port and Transport Economics
MSc Business and Economics

The Network Effects of Truck Platooning:

A Case Study Analysis Focusing on a Supermarket

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Date final version: 2 November 2017

Abstract

Due to the recent financial crisis, many trucking firms are struggling to run their business profitably. To overcome this problem, the firms could lower their operational costs by employing a recent invention called truck platooning. This technology allows trucks, being connected via advanced Wi-Fi connections and radar systems, to drive very closely behind each other, reducing the fuel consumption by up to 10%. If platooning systems of different truck manufacturers are compatible with each other, truck drivers could from platoons on-the-way, resulting in network effects that increase the benefits of truck platooning with the number of platooning trucks. How these network effects develop is investigated via a case study focussing on a supermarket, where the relative short distances between the distribution centre and the stores are considered an approximation for the spontaneous platooning of independent trucks. It is found that the relative reductions in fuel consumption increase with the number of platooning trucks, while up to 6,9% can be saved on fuel costs by the entire truck fleet. The length of the total routes that platooning trucks cover does not affect the relative fuel reduction, whereas the ratio between kilometres driven in a platoon and independently do determine how attractive platooning is. Potential users of truck platooning can be reluctant from employing the technology as it is uncertain whether the first users can save enough on fuel costs to justify the corresponding investment costs. This research shows that supermarkets are able to do so and may belong to the group of suitable first users, as supermarkets meet the characteristics that make truck platooning attractive and beneficial.

Keywords: Logistics, Supply Chain, Trucking, Truck Platooning, Network Effects, Innovation

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1. Introduction

Due to the 2008 financial crisis, the trucking industry has suffered badly during the last decade with a decline in revenue of 17% in 2009 and ever decreasing margins on transportation (Sutherland & Koepke, 2012). Because of the reduced demand for transport, the tariffs have fallen considerably, pressing on the profitability of transportation firms. Many of them have struggled over the last years to run their business in a profitable way, with large numbers of bankruptcies as a result. An ING report (2017), which focuses on the Dutch trucking industry, reveals that during 2016 only 74% of the Dutch trucking companies ran their business profitable. With little influence on the tariffs, thus the revenue side, it may be worthwhile to look for reductions in the costs of trucking in an attempt to improve the margins. A report by TLN (2016) on the Dutch trucking market shows that in 2015 the total costs of trucking consist on average for 21,3% of fuel costs and 48,1% of driver wages, the two largest cost shares. If the costs of trucking can be reduced to increase the margins, it must be in one of these categories as the other costs are inevitable. A recent invention called 'truck platooning' seems perfectly suitable in this attempt.

Since the year 2000, researchers have been working on this technology of truck platooning where two (or more) trucks drive in a platoon and communicate with each other via Wi-Fi connections. The leading truck is operated by a driver; the following truck automatically follows the leading truck at a short distance to reduce aerodynamic friction. Once the first truck brakes, the second truck automatically brakes as well to keep the distance fixed. This technology is said to reduce fuel consumption of the platoon with up to 10%, leading to lower costs and a reduction in CO_2 emissions (Janssen, Zwijnenberg, Blankers, & Kruijff, 2015). The technology is not ready to be used at the moment, but the first commercialization is expected 2020. With adaption of legislation around resting times, truck platooning may also improve the efficiency of driver usage and thus reduce the wage costs. The technology is currently being tested, both within the Netherlands and on international rides.

Clearly, truck platooning is an invention for the transport industry. The question that follows is how this revolutionary technology will be received by the trucking sector. Since truck platooning is new and not exploited by any transportation firm, the invention yields some uncertainty regarding the benefits for trucking companies. The acceptance of truck platooning therefore depends on the diffusion of the invention, as the diffusion determines how trucking companies perceive the invention. In innovation economics, the diffusion model stresses out how innovations are communicated through specific channels towards the potential users of the innovation over time (Rogers, 2002). The diffusion process may be essential in determining the success rate of truck platooning as it explains who adopts the invention and at what moment.

Within the diffusion of an innovation, an important distinction must be made between different adopter categories, persons or organizations that adopt an innovation at different moments of time (Rogers, 1983). Herein, the innovators and the early adopters are the first two categories to adopt an innovation (Rogers, 2002). For truck platooning, any company that performs truck transport on a frequent basis could fall into this category, as long as the technology is beneficial in their eyes. Especially for firms that employ multiple trucks on the same route, truck platooning can result in big reductions in fuel consumption. Therefore, it is likely that firms like these are among the first adopters of the truck platooning invention. Only when truck platooning proves to be successful for these companies, the early and late majority will also adopt the technology (Rogers, 1983; 2002).

The diffusion of truck platooning can possibly be facilitated by realizing that the technology holds great potential for network effects or network externalities. Network effects occur if 'the utility that a user derives from consumption of the good increases with the number of other agents consuming the good'

(Katz & Shapiro, 1985). This is expected to be the case with truck platooning as soon as it is possible to form platoons with trucks of different brands or different trucking companies. After all, the more trucks are equipped with the platooning technology, the easier it is to create a platoon with a 'stranger' and the more fuel is saved. In the ideal case, every truck would be employed with platooning technology, such that a truck driver can easily 'follow' any truck in front of him. Truck drivers that do not know each other can then make a platoon at all times, maximizing the distance that a truck drives in a platoon. This can reduce the fuel consumption of the entire platoon, and thus of the whole truck transport sector, potentially resulting in positive network externalities. Furthermore, as truck platooning results in lower CO_2 emissions, it is possible that the whole society also benefits from truck platooning, resulting in another scope of positive externalities.

Exactly this point will be the topic of this thesis, with the goal of demonstrating whether network effects are present in the truck platooning technology. As said, if this is the case, the network effects can foster the diffusion of this invention and improve the profit rates of trucking companies. Therefore, the main research question that will be answered in the thesis is as follows:

What characteristics of truck platooning can be used most beneficial in order to attract the first adopters of the technology?

It is expected that the network effects of truck platooning contribute largely to the intended reduction in fuel costs. To investigate the degree of network effects that truck platooning potentially holds, a case study of supermarket Hoogvliet will be used. Supplying supermarkets from the distribution centre (DC) usually includes multiple rides over relatively short distances. This is especially the case for Hoogvliet, of which all stores are located in or around the Randstad area (Hoogvliet, 2017). With 1250 rides per week (in 2012) from the DC towards stores, there are sufficient possibilities to combine rides in order to allow truck platooning (logistiek.nl, 2012). The trucks of Hoogvliet will thus be able to drive only short distances in platoons, which is somewhat similar to creating platoons with 'strangers'. The benefit that results for Hoogvliet if it would employ truck platooning for its rides is considered an approximation for the network effects that result from truck platooning in general. By altering the number of trucks that are equipped with platooning technology, it is possible to map the network effects that arise if more trucks are equipped with the technology. Increasing the distances between the DC and the stores, as well as the corresponding distances on the various routes, enables to investigate the impact of distance on the benefits of truck platooning.

To allow the most optimal use of truck platooning, the riding schedule of the trucks of supermarket Hoogvliet must be adjusted. For each number of trucks that are equipped with the platooning technology, new choices should be made to maximize the reductions in fuel costs. This is done via an optimization problem in Excel, which aims to minimize the total fuel costs for each possibility. By rerunning the optimization for different number of trucks with the technology, it is illustrated how the reduction in fuel consumption increases with the number of trucks equipped with the technology. This procedure tries to simulate the network effects of truck platooning. Then, the distances are increased and the problem is again optimized to see the effect of platooning over larger distances. However, a full cost benefit analysis must be performed to investigate whether truck platooning is attractive to be employed. After all, the technology is not free but requires investments to install the technology. Keeping this in mind, an additional analysis is performed where the investments costs are also considered. This analysis reveals that truck platooning yields enough savings in fuel costs to cover the investment costs, but that there is a limit to the maximum number of platooning trucks that a firm should employ.

This research has both academic and practical relevance. It has not been investigated yet what the potential network effects of truck platooning are. The number of articles on network effects in transport or logistics in general is relatively limited. This research may add to this literature base. The topic is also relevant as it looks at truck platooning from an economical point of view, instead of the more common technological perspective. New is that this study focuses more on the implementation of truck platooning over short distances. From a practical point of view, the research may help trucking companies in their investment decisions. The study can reveal the benefits of employing truck platooning on transport over short distances, as it can result in large network effects. This possibly leads to a faster diffusion of truck platooning, as it is more easily accepted by transport companies.

The remainder of this thesis is as follows. First, the literature review will elaborate on economics of innovation. It is then discussed what truck platooning exactly is and how it works. It also explains network effects. The literature review finishes by discussing the hypotheses used to answer the research question. After that, the data and methodology section describes the model used in the case study and what data are used for the models. The outcomes of the models are given in the results section, where the hypotheses are being tested. In this section, a short evaluation of the results is also performed. The thesis finishes with a conclusion.

2. Literature review

Demand for transportation is a form of derived demand and therefore depends on the trade of goods (Rothengatter, 2011). As the global trade in goods dropped during and after the 2008 financial crisis (see figure 1 below), the demand for transportation dropped. Because of the reduced demand for transport, logistic companies saw their freight tariff rates decreasing due to the fierce competition in the market. The pain was also felt by trucking companies all around the world, which had a hard time to run their business in a profitable manner. A report that focuses on the Dutch trucking sector by ING (2017) shows how Dutch trucking companies struggled over recent years to remain profitable. It states that in 2016, a time of recovery, still only 74% of the trucking companies were able to run their business profitable. As the companies themselves have little influence on the tariff rates, they are forced to look for reductions in their costs. These costs consist for Dutch trucking companies on average for 21,3% of fuel costs and for 48,1% of wage costs (TLN, 2016). Together they form a significant share of the total costs and are therefore candidates for cost reductions. One recent invention that can potentially reduce both costs is truck platooning, which is still being tested. As the technology is not used in practice yet, the literature review continues by first looking in more detail at what exactly an innovation is and discusses some main theories regarding innovation. Then a brief overview of truck platooning will be given discussing the basic characteristics and some benefits. Next, the diffusion process of innovation is discussed in more detail. Then, network effects and externalities will be discussed before the literature review finishes with the derivation of the hypotheses.

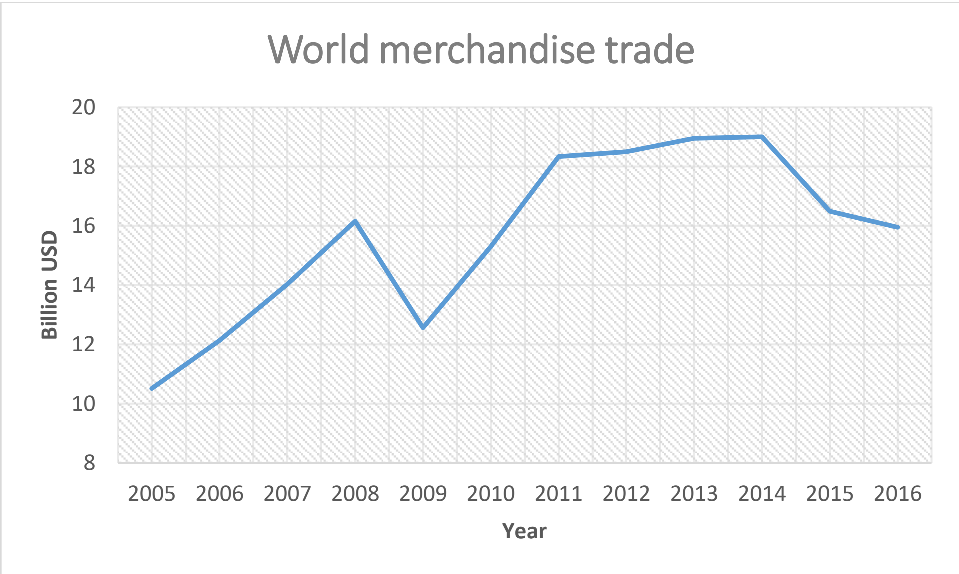

***Figure 1: World merchandise trade over the years 2005 to 2016. Source: World Trade Organization** (2017)*
The graph shows how the world trade in merchandise goods is increasing until 2008, when the crisis develops. A sharp drop can be observed after the crisis, after which the world trade increases again. In 2015, a new drop in world trade can be observed, which continues in 2016.

2.1 Innovation

As truck platooning is a relative recent invention, it may be worthwhile to first shed some light on literature about inventions and innovations. This section aims at doing so, by looking more closely at what innovation exactly is and what characteristics it has. What is the process that innovations follow and where do innovations come from? These are some questions that will be answered in this section.

Innovations themselves are not new, but the literature and stream of science that discusses innovations only started to evolve over the last decades. Clearly, without innovations the world would be entirely different from the world we live in today, but still little attention has been paid to investigating innovations. Historically, economists researching long-run economic growth tend to focus on factors like capital accumulation or how markets emerge and work, ignoring the importance of innovations (Fagerberg, 2004). Of course, the well-known economist Joseph Schumpeter investigated innovations early in the last century, but only during the last decades some research centres and departments have been founded that focus on innovation and its role for economic growth. As innovation is not merely an economic circumstance, innovation is now studied by many scientific disciplines where economics only focus on the right allocation of resources and views the process of innovation as a 'black box' (Fagerberg, 2004).

2.1.1 Invention or innovation

It must be noted first that in science an important distinction is made between the terms innovation and invention. An invention is the first idea of a new product or process, thus when someone thinks for the first time of a new or better product or process. The invention turns into an innovation when the idea is commercialized for the first time (Fagerberg, 2004). It is not always clear whether something is an invention or an innovation, but usually there is a notable lag in time between the two. This lag can take as long as several decades, revealing the issues that may emerge between the working out of ideas and successfully employing the idea in practice (Rogers, 1995). An important aspect herein is that innovations are usually commercialized at firms, whereas the invention can emerge anywhere; not just at firms but also at universities for example. Furthermore, to turn an invention into an innovation, multiple different inputs are required. Examples are knowledge, capabilities, skills, facilities and resources (Fagerberg, 2004).

In this thesis truck platooning is constantly called an invention, as it is not officially commercialized yet. It could be argued that it is already in the phase of being an innovation as many tests on public roads are already performed, but using truck platooning on a commercial basis is not allowed yet due to legislation. Furthermore, the invention still needs some improvements to ensure the safety of the truck drivers and other road users. These are typical examples of lacking conditions that disable commercialization of an invention, which can increase the time lag form invention to an innovation (Fagerberg, 2004). Other possible conditions are that there is not enough market need or that it is currently impossible to further develop or produce an invention because the required materials or techniques are unavailable. This illustrates how complementary inventions or innovations are required to fulfil the development of an innovation.

Quite often, the process of turning inventions in innovations is a lengthy process, sometimes it even is a continuous process (Kline & Rosenberg, 1986). Kline and Rosenberg state that it is a mistake to view innovations as a complete and well-defined end-product entering the market at a certain date. More frequently, they claim, innovations go through continuous changes and modifications during the lifetime of the innovation. The later modifications to the innovation can even be more important than the initial invention that resulted in the innovation.

2.1.2 Types of innovation

Schumpeter made a distinction between five types of innovation: new products, new methods of production, new sources of supply, exploitation of new markets and new ways to organize business (Fagerberg, 2004). The innovation of products and methods of production are considered the most important innovations in the literature. One definition in this aspect is given by Schmookler (1966), who classified product technology as knowledge about the creation and improvement of products whereas production technology is defined as how to produce products. The reason to differentiate between product innovation and process innovation is that the impact of both may be different for the economy. It is believed that product innovations always have a positive impact on the economy via income growth and higher employment rates. Process innovation however often reduces the costs of the input, like labour, and may therefore have a negative impact on the overall economy (Edquist, Hommen, & McKelvey, 2001). Placing truck platooning in one of these categories turns out to be challenging. It is a product that can be installed on trucks and offers a service. It does however alter the process of transportation and thus may be seen as a process innovation.

Innovations can also be classified into a scale of innovativeness, i.e. how radically innovative is an innovation. It was again Schumpeter who identified this classification, where the new innovation is compared with the product or process that is currently in use (Freeman & Soete, 1997). According to this classification, an innovation can be either marginal or incremental, thus small compared to the existing state, or radical, meaning that the new innovation is very different from the existing product or technology. Schumpeter believed that the radical innovations are the most important and have the biggest impact (Fagerberg, 2004). He also described the term technological revolutions, which entail multiple clustered innovations with a big cumulative impact. However, it is claimed that many incremental innovations yield the same or even bigger cumulative impact on the economy and can thus be very important (Lundvall, 1992). The question that arises is how truck platooning should be classified according to this division. This depends on how far the technology is developed and how it is used in practice. As it is now, the following truck still needs to hold an attentive driver to intervene when this is necessary. In this phase and view, truck platooning is only a marginal innovation. However, when the technology is further developed and the legislation allows the driver of the following truck to take his rest, or even be discarded at all, the innovation turns into a radical innovation. In this case, two trucks can be operated by only one driver, which is a big difference compared to the current setup. For other road users, a platoon of trucks may already be seen as radical in the first phase, as the platoon forms a block on the road and thus they need to adopt to this (Janssen et al., 2015).

2.1.3 Creative Destruction

Joseph Schumpeter was the first to consider an evolutionary approach for long-term economic growth where innovation took a major role (Fagerberg, 2003). Schumpeter published multiple books in which he explained the phenomenon of innovation, but his theory of creative destruction is probably the most well-known, published in his book 'Capitalism, Socialism and Democracy' (Schumpeter, 1943). This theory suggests that an innovation replaces an older innovation, or simply product or technology, if the new innovation is better or cheaper. Thus, the old innovation is destroyed once a better version is created. According to Schumpeter, this does not harm the economy by closing existing firms, but instead enriches the economy through new and better firms with better products or technologies (Schumpeter, 1943). The value created by the new innovation must by definition be higher than the value of the old innovation, otherwise the new innovation would not survive. This illustrates how innovation and selection are related as in the Darwinian survival of the fittest (Agarwal, Audretsch, & Sarkar, 2007).

Innovations often emerge from research within a firm or university and is thus the result of private knowledge of people, see for example Agarwal et al. (2007). As a result, the authors of this article claim, creating new knowledge within a firm determines its ability to create wealth through innovations. Agarwal and his colleagues suggest that knowledge spill overs between firms are a key mechanism for new innovation with the help of the theory of creative destruction. Sometimes the knowledge is distributed voluntarily as a form of open innovations, where firms look at each other to benefit from each other's discoveries. In other cases, the knowledge spill over is a result of employees moving from one firm to another, transferring the knowledge that they gained at their former employer to their new one (Agarwal et al., 2007). Sometimes employees even start their own venture to benefit from the knowledge that they gained during their employment to develop an innovation that in their eyes is profitable. Drawing a line with truck platooning, it is easy to see that this innovation is an open innovation where many different parties work together to develop the technology. Multiple original equipment manufacturers (OEM's), research institutes and governments work together while many projects are funded by the European commission (Bakermans, 2016).

2.2 Truck platooning

Truck platooning is a recent invention, a development where multiple research institutes and truck manufacturers or so called original equipment manufacturers (OEM's) work together. The Netherlands plays a major role in the development of this invention, with the involvement of the Dutch government and the Dutch research institute TNO (Dutch Organisation for applied scientific research). The development of truck platooning started some years ago and is still in the testing phase. TNO thinks truck platooning will follow the same path as the introduction of long and heavy truck combinations (LZV) in the Netherlands (Janssen, Zwijnenberg, Blankers, & Kruijff, 2015). Experimentation with LZV's started in the year 2000. In 2006, the first tests were performed and in 2012 an official approval was given for the combinations (Rijkswaterstaat, 2010). In order to allow truck platooning on the Dutch public roads, some adaption in the legislation is required. TNO expects that this process will be finished by 2020. From that year onwards, commercially driven truck platoons consisting of two trucks will be visible on the road whereas longer platoons will only start emerging after 2030, according to TNO (Janssen et al., 2015).

With truck platooning, two or more trucks drive in a platoon, being connected with each other via advanced Wi-Fi connections. The focus in the development of truck platooning currently lies on platoons consisting of two trucks only, so this report will be limited to platoons of this length. The trucks in the platoon communicate with each other, such that the following truck knows when the leading truck brakes. Via the connection, a fixed distance between the trucks can be achieved that reduces the aerodynamic friction of mainly the following truck. The distance is currently set at 0,5 seconds, but will be reduced towards 0,3 seconds in the future, implying a gap of about 6,7 meters when the trucks drive at a speed of 80 km/h (Janssen et al., 2015). The leading truck must be operated by a human driver, whereas the driver of the following truck is not required to be attentive during the ride. This gives the following driver the opportunity to have a rest (once this is allowed by legislation) or to perform other activities like administration. As the leading truck is still operated by a human driver, truck platooning is not the same as autonomous driving, where no driver is needed at all. Truck platooning focuses on enabling communication between vehicles.

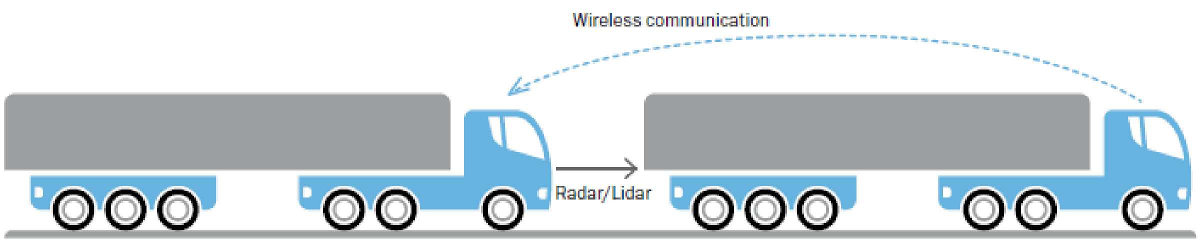

Figure 2: The connection between platooning trucks. Source: Janssen et al. (2015) p.7
The illustration shows how two trucks communicate with each other while platooning. A wireless connection via an advanced Wi-Fi connection is set up which lets the following truck know when the leading truck is braking. Via Radar and Lidar sensors, the following truck measures the distance between the trucks and tries to keep it fixed.

To enable the creation of a platoon, two trucks are required on the same route that are both equipped with truck platooning technology. This includes a wireless connection between the trucks via advanced Wi-Fi technology and radar and LIDAR technology that constantly measures the distance between the trucks (Janssen et al., 2015). Keeping the speed of the platoon and the distance between the trucks fixed is achieved via Cooperative Adaptive Cruise Control technology (CACC). This technology is able to deal with other road users as well, for example when the platoon is overtaken by a car. In this instance, it adopts the speed of the entire platoon, as well as the distance between the two trucks. Because automatic software is used, the response time of a human driver is eliminated, which allows the trucks to drive so close to each other. The connection is shown in figure 2. As said, creating a platoon requires (at least) two trucks on the same route. In the future, TNO expects that on-the-fly platooning will become reality, where a truck driver can simply join or start a platoon with other truck drivers, thus also with competitors (Janssen et al., 2015). This development reduces the dependency of the trucking company upon its own fleet and routes, but enables wider use of the technology.

For the development and implementation of truck platooning, multiple stakeholders are involved. First there are the developers of the technology and the truck manufacturers who need to install the technology on the trucks. One can also think of tier suppliers, who deliver loose parts, as to install the technology on already employed trucks. Next there are policymakers like governments and ministries who need to adopt the legislation around trucking in order to allow truck platooning on public national roads. Other regulators also play a role like local authorities, the road infrastructure manager, inspection and customs. Insurers need to think about new ways to determine the liability after a crash. Who is responsible if something goes wrong with a truck platoon, the software or the leading truck driver? Finally, but probably most importantly, the (potential) users of the truck platooning technology are also large stakeholders. They determine if and how to use the technology and are in the end the customers of the developing firms and truck companies. Among the users are shippers, carriers or other yet to be developed platooning service providers (Janssen et al., 2015).

There are numerous applications of which one can think of for truck platooning. For transport over longer distances, truck platooning can significantly increase driver efficiency. If a transport firm has two trucks on the same route, or it can cooperate with another firm on that route, the drivers of the trucks can work in shifts. First one driver leads the platoon, while the other driver takes his rest. After some hours, the drivers change position while the first driver takes his rest and the second driver leads the platoon. This can save a transport firm on wage costs, as the trip is completed in less time (Janssen et al., 2015). Other applications are the rides between multiple locations of the same firm. Janssen and his colleagues (2015) for example describe how ECT can use truck platooning to transport containers from the Euromax terminal to the X-ray scanner, 16 kilometres away on the second Maasvlakte. Another example that they give is Peter Appel transport, which is responsible for around 100 shipments from the central distribution centre of supermarket Albert Heijn towards the four local DC's. There are of course many more applications for truck platooning, but they are not all discussed here as this is not the focus of this study.

The application examples for transport over longer distances illustrates how truck platooning can help transport companies reduce their labour costs. Drivers can be used more efficiently, with as a result that it takes less time to complete one ride. The driver of the following truck can have a rest while still being on the move. Based on interviews with carriers, Janssen and colleagues (2015) estimate that this can save up to 45 minutes per driver per day. In the future, it could even be the case that there is no driver in the following truck, such that one driver can control two trucks at the same time. More importantly are the reductions in fuel costs that can be achieved via truck platooning. The SARTRE project, financed by the European commission, claims that the fuel consumption of the following truck will be reduced with 8% to 13%, while the fuel consumption of the leading truck also decreases with 2% to 8%. Based on these numbers, the project estimates that the average reduction in fuel consumption over the entire platoon is 10% per truck (Davila, 2016). With a 10% reduction in fuel consumption and thus in fuel costs, even when legislation around resting times is not adapted, platooning can still reduce the total costs. Therefore, it may be a potential solution for the problem illustrated in the introduction.

Besides fuel reductions and more efficient driver usage, both benefits for the transport firms, the society can also benefit from truck platooning. Firstly, the reduction in fuel consumption leads to a reduction in CO_2 emissions, a very actual topic that many transport companies focus on. Lower CO_2 emissions benefits the whole society, including future generations. It is estimated that the reduction in CO_2 emissions equals 10% (ACEA, 2016). Truck platooning also leads to more road capacity, as a platoon uses less space than two manually driven trucks. Driving at 80 km/h and using a gap of 2 seconds between trucks, two manually driven truck have a total length of 82 metres against 44 metres of the automated truck platoon (Janssen et al., 2015). Furthermore, truck platooning improves road safety for both truck drivers and other road users. Human errors are on the basis of 90% of all traffic accidents (ACEA, 2016). Truck platooning may be able to avoid some of these accidents. Finally, truck platooning may benefit the society as it enables goods to be delivered faster, helping the supply chain to be optimised (ACEA, 2016).

As is the case with many innovations, truck platooning also holds some limitations and risks. One important aspect herein is that other road users need to get used to the situation of a platoon on the road (Bergenhem, Huang, Benmimoun, & Robinson, 2010). Especially when one wants to enter or leave the highway, a wall of platooning trucks can be troublesome. Since the distance between two trucks is relatively small, road users may find themselves incapable of crossing the platoon. When the length of the platoon is increased to more than two trucks, this issue gets even more important. As mentioned before, determining who is liable when something happens with a truck platoon can also be a problem. Furthermore, some barriers towards the implementation of truck platooning can be thought of. Janssen and his colleagues (2015) divide the risks and barriers towards the implementation of truck platooning into six categories, namely: business, deployment and timing, legal and conditional, safety and security, technology and user acceptance. For more details on these barriers, it is referred to the report by Janssen et al. (2015). More practical barriers are discussed in Bakermans (2016).

It is proposed to create a truck platooning service provider which acts as a central point of coordination (Bakermans, 2016). This service provider enables the linkage between multiple independent truck drivers to help them form a platoon. Via the provider, the benefits of truck platooning can be distributed over all participants. When two (or more) trucks with a destination close to each other drive apart from each other with a certain distance between them, say 10 kilometres, the service provider may couple the trucks in order to create a platoon. The first truck will then have to drive a bit slower, while the following truck must cover the 10-kilometre gap. Then, both trucks can benefit from driving in the platoon, such as reduced fuel consumption and eventually less idle driver time in the future. One can think of this service as an air traffic controller on airports, coordinating all the different air traffic streams.

The service provider may turn out to be necessary to enable truck platooning on-the-fly or to foster trust between different carriers (Janssen et al., 2015). The service provider then makes sure that the insurance is arranged properly and that the maintenance reports are exchanged. Of course, this service is not free, but truck drivers or carriers must pay to be part of the network which can hold some carriers back if a platooning partner is not guaranteed. The service provider on the other hand benefits if the pool of participating carriers of truckers is larger, such that it can match more trucks into a platoon and increase their fees.

2.3 Diffusion of innovation

After discussing the most important aspects of innovation, it will now be discussed how innovation diffuses to the market with potential users of the innovation. After all, to be commercially successful, the innovation must first be adopted by the users. Previous literature shows that many innovations in the information technology sector, under which truck platooning falls, reach the phase where they are acquired by firms but nevertheless never reach the phase of being fully used. For example, Fichman and Kemerer (1999) give one short overview of studies related these kinds of innovations. It is therefore relevant to assess how innovations like truck platooning are received and adopted by the (potential) users, which is done in this section.

2.3.1 Rogers's model of diffusion

The most widely applied model for diffusion of innovation is the diffusion model stressed out by Everett Rogers in his book *Diffusion of innovations*. In this model, diffusion is described as "the process through which (1) an innovation (2) is communicated through certain channels (3) over time (4) among the members of a social system" (Rogers, 1995). It is thus the communication of new ideas or new products and must represent some degree of uncertainty for the individual or organization receiving the message (Rogers, 2002). Rogers claims that the communication process is twofold: both parties that are part of the conversation exchange information with each other. The information that is shared can reduce the uncertainty for the buying person or firm and is thus a valuable component in the communication process. The communication enables the innovation to diffuse, and then leads to the adoption of the innovation. In this sense, diffusion can be seen as some sort of social change, which Rogers defines as "the process by which alteration occurs in the structure and function of a social system" (Rogers, 1995). The latter definition is basically the adoption of the innovation.

As can be seen from the phrase above, Roger's definition of diffusion in this theory consists of four elements. The first element of innovation is simply the product or process, or even only the idea that is new for the person or firm reaching the message about the innovation (Rogers, 1995). The reaction of the individual is determined by how new the innovation in his eyes is. The individual may have also already heard about the innovation before, but rejected it at that time. More information about what an innovation exactly is was given in section 2.1.

The second element is the communication channels via which the innovation is communicated. Communication is herein defined as the process of creating and sharing information. Communication channels are then, as logically follows, the ways how the information is sent from one to another. Of special importance in the determination of the communication channel is the relationship that the involved parties have with each other (Rogers, 1995). Mass media channels can be used if the seller of the innovation wants to reach a large audience to create awareness or knowledge about the innovation. More personal contact via face-to-face communication, or so called interpersonal channels, is more desired in the final phase of sharing information or changing an attitude about an innovation (Rogers, 2002). It is the latter kind of information that will most likely be used to reach the potential users of the truck platooning invention.

The third element is time, a variable ignored in many other behavioural theories. The role that time plays in diffusion is threefold in Rogers' theory. First, some time goes by between the time that someone gets to know about an innovation for the first time and the moment that he really adopts or rejects the innovation. This innovation-decision process will be explained in more detail later in this section. Time also plays a role in how innovative a person is, thus how fast or slow does the person adopt the innovation compared to others. More on this will be explained later in the paragraph about adopter categories. Finally, time is involved in the rate of adoption of an innovation. This rate is defined as the number of people within a society that has adopted the innovation during a certain period of time (Rogers, 1995).

The last element is the social system or the society in which the innovation is placed. The exact definition of the social system given by Rogers is: “a defined set of interrelated units that are engaged in joint problem solving to accomplish a common goal” (Rogers, 1995). The social system consists of various members such as individual persons, informal groups, organizations and other smaller sub-systems. The social system can thus exist of consumers in a market or firms that are active in a certain industry. Clearly, the social system of truck platooning is the trucking industry, with transport companies as members of this system. However, Rogers claims, the members within a system are not all the same. The members can be divided into a certain structure with groups of comparable members. Within a social system, opinion leaders may exist, these are persons or organizations with a strong influential force on the decisions of other members. These opinion leaders can sometimes make or break an innovation.

2.3.2 A broader definition of diffusion.

Katz, Levin and Hamilton in 1963 gave an even more complete definition of diffusion and describe the process of diffusion as “the (1) acceptance, (2) over time, (3) of some specific item, (4) by individuals, groups or other adopting units, linked (5) to specific channels of communication, (6) to a social culture and (7) to a given system of values or culture” (Katz, Levin, & Hamilton, 1963). This definition consists of seven elements as can be seen from the quote above. The core of this larger definition is essentially the same as Rogers’ definition, except that it also introduces the element of acceptance. The element of the social system is here subdivided into three different aspects; elements 4, 6 and 7.

The additional element ‘acceptance’ is seen as the dependent variable of the definition in many studies that focus on diffusion (Katz et al., 1963). Acceptance is highly related to the element of time in Rogers’ definition and describes the time when an innovation is accepted. How acceptance should be defined is a bit arbitrary. Usually, the first use of an innovation is seen as acceptance of the innovation, even though this does not always lead to continued use of the innovation. In the latter case, the question arises whether the innovation is really accepted or only tried. Therefore, a distinction should be made between trial and full adoption of an innovation. This often turns out to be troublesome in practice. Therefore, Rogers’ definition is more frequently used in the literature, as will be done in this report.

2.3.3 Characteristics that determine rate of adoption

The speed of the diffusion of an innovation depends on five characteristics, namely: (1) relative advantage, (2) compatibility, (3) complexity, (4) trialability and (5) observability. Innovations that score higher on characteristics 1, 2, 4 and 5 and lower on 3 will be adopted more rapidly (Rogers, 2002). Relative advantage describes to what extent an innovation is perceived better than the status quo. This advantage can be economical, convenience, satisfaction or the social prestige that the innovation gives. Important herein is how the potential user perceives the advantage, not how the creator of the innovation perceives the advantage (Rogers, 1995).

Compatibility describes to what degree an innovation is compatible to the status quo. This can be how consistent it is with values of existing products or technologies, the needs of the potential users and their past experiences. If an innovation is compatible with current technologies, it is easy to use and therefore likely to be adopted earlier. On the other hand, if the innovation is not compatible, users need time to adapt to the new technology or even need to change their value system. Related to compatibility is the complexity of an innovation, which depicts how difficult an innovation is to use or implement. A marginal innovation is usually less complex to understand than a radical innovation. Innovations that are very complex will need more time to be adopted, where innovations that are straightforward in their usage are adopted faster (Rogers, 1995)

The character of trialability describes how easy it is to only try an innovation without fully implementing it. Potential users may want to experiment with the innovation first before they buy it. Innovations that are easier used in a trial version will be adopted quicker than innovations that need full adoption to be tried. The trialability reduces the uncertainty of the potential users. Finally, the character of observability determines how visible using the innovation is for others. If the results of using an innovation are easily visible, other potential users will ask the user of the innovation about it and may also start to use the innovation. In this case, the innovation diffuses quicker (Rogers, 1995).

2.3.4 Adopter categories

The innovativeness of a person or organisation was already mentioned before and explains how early that person or organisation adopts an innovation compared to other members in a social system. By using a normal curve, five different adopter categories can be distinguished, see figure 3. Two standard deviations before the mean is the group called innovators. Between two and one standard deviation before the mean is the group of early adopters. Starting at one standard deviation before the mean is the early majority, with the late majority being the next group up to one standard deviation after the mean. Finally, beyond one standard deviation after the mean is the group of laggards. In his book, Rogers (1995) shows how the distribution of individuals adopting an innovation follows the normal curve for many innovations. Therefore, this division is frequently used. Whether this model also applies to truck platooning cannot be said now; no research on this topic is performed and as the invention is not yet commercialized, it cannot be estimated.

The innovators, the first 2,5% of a social system to adopt an innovation, are very eager to try new ideas. The people in this category often form their own community, with many of their peers being part of cosmopolite social relationships (Rogers, 1995). Still, the innovators may be located far away from each other. The innovators like the riskiness of new innovations and thus must be willing to accept when an innovation flops. Rogers describe innovators as venturesome. The next category are the early adopters, who are according to Rogers more integrated into the local social system and therefore described as respectful. As a result, this category has a lot of opinion leadership, delivering many opinion leaders for later categories. They consist of 13,5% of the total social system and many potential users of the innovation looks at this category for their choice of adoption.

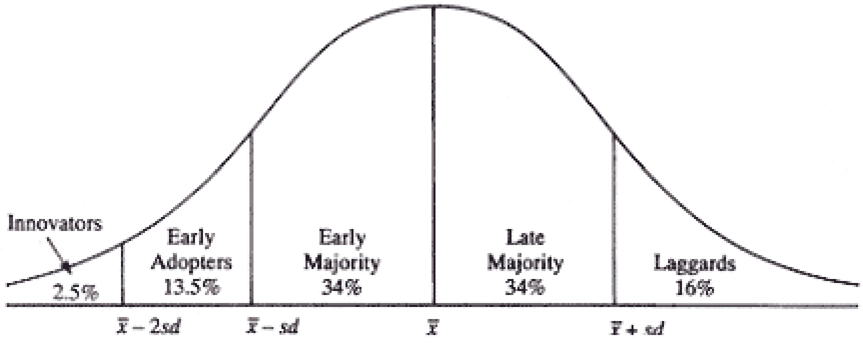

Figure 3: Adopter categories. Source: copied from *(Stephenson, 2003)*
The standard normal curve showing the five different adopter categories, based on a division between two standard deviations before the mean to one standard deviations of the mean. These borders are shown, as well as the percentage of individuals of a social system being (on average) part of each category.

The early and late majority, both responsible for 34% of the social system, are the next two categories to adopt an innovation. The early majority is described as deliberate and are not among the opinion leaders. They are important in the diffusion of an innovation as they are the first large group of adopters. The late majority is more sceptical about an innovation and only adopts a new idea after the average member of a social system has done so. As they are a large portion of the social system, they too are important for the diffusion of an innovation. Finally, the laggards consisting of 16% of a social system are described as traditional buyers. They are the last to adopt an innovation, running the risk that the innovation is already obsolete at the moment of purchase.

It is questionable whether this categorization also holds for innovations that will mainly be used by professionals and firms, like truck platooning. Still, the distribution of categories can be very important when bringing truck platooning to the market. Bakermans (2016) mentioned that one of the barriers of implanting truck platooning is that the first users may find it hard to reap the harvest. He claims that no or little first-mover advantages are present, only when one company employs multiple trucks on the route on the same time. Section 2.4 will go deeper into this problem, but this shows that it can be important to investigate who the innovators and early adopters will potentially be.

Quite soon after Rogers published the first edition of his book (the reference Rogers, 1995 refers to the fourth edition of his book), Thomas Robertson (1967) righteously claimed that the distribution illustrated above assumes an adoption rate of 100%. He raises the question whether this model is then valid to describe the diffusion process of an innovation. Robertson claims that for many, if not all innovations, not everyone will adopt it, simply because the innovation is not always (perceived) superior to the status quo. Therefore, he proposes that an incomplete curve should be used instead of the normal curve. A new question that arises then is whether this is relevant for innovations that still need to be brought to the market. An innovation can also be not adopted at all, or only by few.

2.3.5 Innovation-decision process

If someone or a firm considers adopting an innovation, or only gets in touch with an innovation, they go through the innovation-decision process, a mental procedure. Rogers splits this process into five phases and defines the innovation-decision process as "the mental process through which an individual (or other decision-making unit) passes (1) from the first knowledge of an innovation, (2) to forming an attitude towards the innovation, (3) to a decision to adopt or reject, (4) to implementation of the new idea and to (5) confirmation of this decision" (Rogers, 2002). As can be observed from the quote above, an individual goes through a series of actions on determining whether to adopt an innovation or not. During the decision, the individual has to cope with the uncertainty that is related to the innovation and especially arises if the innovation is adopted (Rogers, 1995).

Obtaining the first knowledge of an innovation occurs once someone is for the first time exposed to the innovation and starts to understand the functionality of the innovation. In the next phase, the person will form a first attitude towards the innovation. This persuasion can be either positive or negative. Depending on the attitude that is created, it is chosen whether to adopt or reject the innovation. Only if the person chooses to adopt the innovation, he will continue to the process of implementing the innovation in its function. Once the innovation is put into use, it is evaluated whether the innovation meets the expectations and results in the desired benefits. If it doesn't, the person can decide to return to the situation preceding the implantation of the innovation. This can eventually result into a re-invention (Rogers, 1995).

2.3.6 Assimilation gap

It was already mentioned that the term acceptance of an innovation is troublesome as someone who only tries an innovation does not necessarily implement the innovation (Katz et al., 1963). If someone decides to adopt and implement an innovation, he will first need to buy it. Still then, a distinction can be made between the moment that someone buys an innovation for the first time and the moment he uses it. It is very likely that there is a certain lag between the two events. This is especially the case for organizations buying information technologies, where time is essentially required to adopt the processes within the organization (Fichman & Kemerer, 1999). This means that there is a lag between the acquisition and deployment of an innovation, which may lead to problems in realizing an adoption curve. This gap can even be increasing over time when looked at cumulative numbers over all absorbers. Fichman and Kemerer (1999) call this the assimilation gap, which can result in wrong conclusions during the diffusion process. An illustration of the assimilation gap is shown in figure 4.

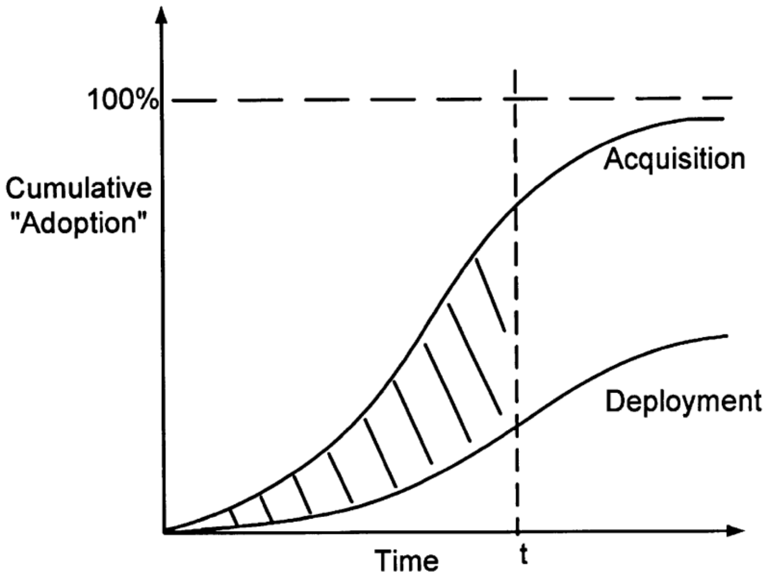

Figure 4: The assimilation gap illustrated. Source: copied from *(Fichman & Kemerer, 1999)*
In this graph, the hypothetical cumulative adoption of an innovation is split into an acquisition and deployment curve, graphed over time. The assimilation gap is the difference between the cumulative acquisition and cumulative deployment curve. At time t *the assimilation gap equals the dashed area.*

Some innovations are more sizeable for assimilation gaps than others. Reasons for assimilation gaps to occur are for example high knowledge barriers, leading to slow diffusion and lower deployment rates (Attewell, 1992). In this case, organizations need to learn more about the new technology via new knowledge and skills before they can successfully implement it. It could also be the case that organizations expect to gain more from using the innovation in the future instead of directly (Cohen & Levinthal, 1990). Yet another reason for an assimilation gap to occur is that an organization expects to realize increasing returns to adoption (Fichman & Kemerer, 1999). An innovation has increasing returns when the benefits for one are higher the more people use it (Arthur, 1996). The increasing returns are a result of network effects that may be achieved. Section 2.4 is devoted to discussing network effects and their importance for the diffusion of innovations, as truck platooning holds great potential for possible large network effects.

2.4 Network effects

It has been mentioned several times during this literature review that truck platooning holds potential for network effects. What exactly network effects are and how truck platooning may contain network effects will be discussed in this section. Referring to section 2.3, it could be that network effects foster the diffusion of truck platooning. Whether users of truck platooning should pay for benefitting from the network effects is a possibility as will be discussed later in this section using the Coase theorem.

2.4.1 What are network effects

Some goods have little value in isolation but the utility that can be derived from that good increases once more people, or agents, use that particular good (Katz & Shapiro, 1985; 1986; 1994). That means that a product becomes more useful if you are not the only person using the product, but other people use it as well. The classical textbook example to illustrate this idea is the telephone. Being the only person in the world who owns a telephone makes the device useless, after all there is no one to call with that telephone. As soon as family, friends and others also buy a telephone, the person will derive more utility from the device as it can be used to call these persons. The telephone becomes even more valuable once more people buy a telephone, such that virtually any person can be called. Thus, the more people use the telephone, the more valuable owning a telephone becomes.

Katz and Shapiro (1985) specify three reasons for which network effects may occur. First, consumption externalities can result from direct physical effects that rely on the number of purchases or uses for a product. This effect is explained in the telephone example above. Second, indirect effects can also result in network effects. For example, if more people buy a product of a certain type or brand, one can expect that the additional products related to this initial product will be better or supplied in more variety. This is the so-called hardware-software paradigm, explained in more detail in the next paragraph. The third reason is that consumption externalities for durable products result because if more people buy a product of a certain type of brand, the after-sales service for that brand will be better or cheaper. An example for this effect is the automobile industry, where consumers tend to favour brands that are already popular in their country over relative new or unpopular brands. The popular brands usually have a more extensive service network with many garages that can fix the car if it is broken, with spare parts being widely available.

The hardware-software paradigm mentioned above arises when two products on their own offer little value but together are more valuable (Katz & Shapiro, 1994). They form a system where the hardware is required to use the software, but without the software the hardware is worthless. An example is a DVD player, where the DVD player is the hardware to play DVD discs, the software. Quite often in such systems, the hardware is bought before the software. That means that consumers must think about the price, quantity and quality of software that will be available in the future for the hardware of a certain type or brand when buying the hardware. When combinations of hardware and software of different brands are compatible, this problem is less relevant. With incompatibility consumers wish to choose for the hardware type that employs the best software in the future as switching can be costly.

A system, or more specifically hardware, that is superior can obtain dominance in the market and may result in a monopoly once the system is adopted by (most) of the market. This gives an incentive for large established firms to make their components of the system incompatible, whereas smaller firms favour compatibility (Katz & Shapiro, 1994). A model which depicts a few suppliers competing for a system is given in Katz & Shapiro (1985). The result of the model is that consumers' expectations in markets with network effects are important for which type or brand of system wins. In the case of incompatibility of components of a system, the firms' reputations determine which system wins. A more competitive market focussing model for the adoption of a certain technology is given in Katz & Shapiro (1986). With this model, it is found that the market undersupplies compatibility and that the technology that is superior today enjoys a competitive advantage. When firms decide to sponsor their systems, the system that receives the most sponsorship is likely to win. However, when two competing systems are sponsored, the efficient outcome results where the technology that is superior in the future has an advantage.

2.4.2 Truck platooning and network effects

What are then the network effects that may potentially be found for truck platooning? To employ truck platooning, two trucks need to drive at least on the same road, preferably on the same route. Otherwise no platoon can be made. Now imagine that every truck on the road is employed with platooning technology. That is, any truck driver can form a platoon with any truck driving in front of him. It is then no longer needed for a trucking firm to operate two trucks on the same route, as there are platooning opportunities available over the entire route. What is essential in this problem is that if a truck driver is the only person who installed platooning technology, the technology is worthless. Thus the first user of the technology may find it hard to benefit from using the technology, unless it employs multiple trucks on the same route. When more trucks are equipped with the platooning technology, the technology will gain value. Still, the exact value depends on the number of surrounding trucks with the technology installed and their destinations. Eventually, via the advanced Wi-Fi connections, truck drivers can share their destination to evaluate to what extent their 'partner' is suitable to form a platoon with. Or, via the truck platooning service agency described in section 2.2 truck drivers could find appropriate platoon candidates nearby.

In any case, the core of the message is that independent truck drivers on the road benefit more if more truck drivers have the truck platooning technology installed on their trucks. In this case it becomes easier to create a platoon, and thus the value of the technology increases. This means that opportunities for network effects are present. This requires of course that the different platooning technologies of different truck brands are compatible with each other. Herein, trucks can be seen as hardware and the truck platooning technology as software. Full compatibility of both hardware and software is required to successfully benefit from the network effects that platooning may provide. The benefits that result from the network effects is a reduction in fuel consumption and reduced CO_2 emissions. Eventually, the driver of the following truck may also benefit from the time that becomes available when he is not operating the truck, by doing administrative tasks or having a rest.

2.4.3 Externalities

More externalities may result, also for agents in an economy who are not necessarily the user of a product. These externalities may either be positive or negative. Negative externalities for example occur when a factory pollutes the air in a region, such that people living around the factory have struggles with their health (Ayres & Kneese, 1969). In the same context, an example of positive externalities occurs once the factory employs new technology, resulting in lower pollution. The people living nearby then benefit from cleaner air. In both cases, the people living around the factory are no direct users of the production (except employees or some consumers), but still they are influenced by the factory. This example illustrates a production technology, but the same applies to products being used by either companies or consumers.

Trucking itself naturally results in multiple negative externalities. Pollution, collisions, congestion and using up road capacity are some examples. Truck platooning, however, may result in positive externalities even for people not using the technology. Some examples mentioned in section 2.2 are increased safety, better throughput on roads, less CO_2 emissions and better use of the capacity of roads. This last aspect was investigated in a study that made a simulation using real traffic data of the A4 nearby Schiphol (Arem, Driel, & Visser, 2006). The authors found that in the case when cooperative adaptive cruise control (CACC) technology was used, an improvement was observed for the stability of the traffic flow and its efficiency. The throughput was higher for roads where CACC equipped vehicles were used, though the size of the effect depends on the share of vehicles that use CACC technologies. Truck platooning may thus result in positive externalities, but as they are not the focus of the study, while network effects are, no more attention is paid to the externalities.

2.4.4 Coase theorem

The Coase theorem is a well-known theorem under economists developed by Ronald Coase in his paper 'The Problem of Social Cost' (Coase, 1960). The main point made in this paper is that efficient use of resources does not require competitive markets. Instead, people or agents can deal with inefficient market outcomes and negotiate towards a more efficient outcome (Farrell, 1987). Theoretically, the outcome of the negotiation is always efficient, otherwise people would continue negotiating until a better outcome is achieved. When everything related to the situation can be traded with each other or sold for money, the result of the negotiation should always be Pareto-efficient. The agents involved in the negotiation are not simple price takers, but employ their power to achieve better prices. This is different from the welfare theory which states that under perfectly competitive markets, an efficient equilibrium will result if all the involved agents handle in their own best interest, thus being selfish (Farrell, 1987). There is unfortunately not always a competitive market to achieve the best outcomes and the Coase theorem explains how an efficient outcome can then be obtained.

To illustrate how the Coase theorem works, an example that Ronald Coase used in his paper will be used (Coase, 1960). This example is close to the standard example of noisy neighbours used in student textbooks, like Frank and Cartwright (2013) where the following example is also used. In this example, a doctor and a confectioner live next to each other. The doctor needs silence to examine his patients, but the silence is disrupted by the noisy machinery of his neighbour. The noise of the confectioner harms the doctor, but forbidding to use the noise machinery harms the confectioner. Thus, no matter what the outcome after negotiating is, someone will always be harmed. Now suppose that the confectioner benefits 40 by making noise, while the cost of the noise for the doctor is 60. Dependent on who is made liable, the two parties will start negotiating to discuss some form of compensation. If the confectioner is liable and continues making noise, he will have to compensate the doctor with 60, which is more than the 40 he loses when discontinuing operations. In this case, it is natural that the confectioner stops his operation without paying anything to the doctor and the doctor still gets 60. If the doctor is made liable, he must compensate the confectioner 40 to have him stop making noise, but will gain 60 by examining his patients, which is higher. In this case, it is possible that the doctor pays the confectioner a certain amount of money to compensate for the loss, which is at least 40 but no higher than 60. The exact figure depends on how good both parties are in negotiating.

The details of the example can be varied in various ways; by changing the liability, modifying the costs and benefits of both parties or introducing an additional option where one of the parties can make some sort of adjustment as to reduce the costs of the nuisance. In all cases, the exact outcome depends on how good both parties can negotiate. It assumes however that both parties are perfectly informed and know everything about each other. That is, the benefits that the other has from the other's own operations and the costs of the harm of that person's operation. In reality, this seems highly unlikely, instead it could be harmful to give the other party all the information. Even when property rights exist, it is still likely that some private information remains (Farrell, 1987). Where the costs of negotiation are high and/or the benefits small, it is also possible that no accordance occurs (Frank & Cartwright, 2013).

While the Coase theorem mainly focusses on negative externalities, it can also be adjusted to be used for positive externalities. For example, if one person benefits if someone else does or uses something specific, but that person himself does not benefit (enough) from it, the first person could compensate the latter person in order to have the latter person use or do it. This can be used in the diffusion of truck platooning. As Bakermans (2016) mentioned, the benefits of the first users of truck platooning are limited which may cause them not to implement truck platooning at all. However, for some trucking companies it may be beneficial that there are many trucks on the road that have truck platooning technology, making it easier to form a platoon. If the benefits are high enough, these companies may possibly be willing to pay some money in order to enable the creation of platoons. Of course, it is impossible to pay money to every trucking company that exists as this is too expensive. However, via a fee for the truck providing service agency described in section 2.2, the companies may find themselves able to create a platoon. To an extent, this fee can then be seen as the compensation that one of the parties needs to pay in the Coase theorem. But now instead of compensation for the harm that one imposes on the other rather as motivation such that one can benefit from the other.

2.5 Deriving hypotheses

To answer the research question proposed in the introduction, two hypotheses are formulated. The hypotheses are, as usual, based on the literature review discussed above.

Assuming that truck platooning yields a positive effect on the fuel consumption and the costs of trucking, the first hypothesis focuses on investigating whether truck platooning yields network effects. If network effects are present, the savings in fuel should increase with the number of trucks that are equipped with platooning technology. For individual truck drivers, the costs of installing the technology are in this case sunk costs, placing the focus on the saving in fuel costs. This results in the first hypothesis:

Hypothesis 1: *There is a positive relation between the number of trucks equipped with platooning technology and fuel consumption reductions.*

The next hypothesis focuses on truck platooning over longer distances, which may be useful for the truck platooning service provider. Via the service provider, truck drivers can find suitable platooning partners to form a platoon with, as to drive in a platoon over a longer distance. In order to make it attractive for individual truck drivers to sign in to a service provider, the benefits that result from this service should accrue with the distance that the trucks can drive in a platoon at a time. One can expect that driving in a platoon over a longer distance will result in larger fuel consumption reductions. This expectation leads to the second hypothesis:

Hypothesis 2: *There is a positive relation between platooning distance and fuel consumption reductions.*

3. Data and methodology

To investigate whether truck platooning holds network effects, a case study with related analyses will be performed. The case study focuses on a Dutch supermarket chain called Hoogvliet. The exact data that will be used for the case study will be discussed first in this chapter. A model is made in Excel that aims to optimize the freight schedule for Hoogvliet, ensuring that as much as possible fuel is saved via truck platooning. Varying with some of the input data of this model allows the investigation of the hypotheses. The methodology for this model is discussed in detail in the second part of this chapter. Finally, the costs of implementing truck platooning are shortly discussed to allow a cost-benefit analysis.

3.1 Data case study supermarket Hoogvliet

As was noted before, potential first users of truck platooning may be firms that transport goods on fixed routes and on a frequent basis, while employing multiple trucks. These kinds of companies are able to benefit from truck platooning independently, without relying on different trucking companies. This requires however that the routes of the different trucks have at least some part in correspondence. Supermarkets, who supply their stores from one or several central distribution centre(s), fit into this profile. Usually, the stores receive multiple loads per day whereas stores can be located relatively close to each other. These characteristics feed the possibilities of truck platooning. Therefore, this research uses a case study focussing on supermarket Hoogvliet to see how truck platooning affects the fuel consumption with the aim of mapping the network effects of truck platooning.

Hoogvliet is a chain with 67 stores that are all located in or around the Randstad area. This ensures that multiple stores are located relatively close to each other, meaning that they must have a rather large corresponding share of the distance that is covered from the distribution centre to the stores. Hoogvliet uses one distribution centre to supply all its stores, which is centrally located in the city Alphen aan den Rijn. For the case study, a selection is made of 40 stores that are all located to the west of Alphen aan den Rijn or inside Alphen aan den Rijn. This selection reduces the size and complexity of the problem to be investigated, while encouraging that many routes correspond with each other for a large share. The map in figure 5 below shows the locations of the included stores in blue arrows and the distribution centre with the red arrow. Of course, the case study could simply be extended to include all Hoogvliet stores. However, the majority of the Hoogvliet stores are located to the west of Alphen aan den Rijn and are included in this analysis, providing a useful basis for the study. A table showing the addresses and further details of all the stores is included in the appendix. To keep a clear overview during the remainder of the analysis, each store is given an ID number. With over 1250 rides per week in 2012 between the distribution centre and the stores (logistiek.nl, 2012), there should be enough possibilities to combine rides as to allow truck platooning.

Figure 5 shows that some of the stores are located very close to each other. Intuitively, this means that a large share of the routes from the distribution centre towards the stores must be the same. These corresponding distances are essential for determining how Hoogvliet can use truck platooning in order to reduce fuel costs. For each of the 40 stores, the routes are determined using Google Maps. Then, a 41x41 matrix is set up that contains the corresponding distance for each existing pair of stores. There are 760 unique pairs and for each pair it is looked up via Google Maps what distance of their route is equal. For example, for stores 1 and 2, ‘s-Gravenzande and Monster respectively, both routes go via the A4 and take exit 12 towards Den Haag south continuing on the N211. Only halfway the N211 an exit must be taken by the truck going towards Monster, whereas the truck going to ‘s-Gravenzande continues driving on the N211. Up to this point, the routes towards the stores are the same, which covers according to Google Maps a distance of 40,3 kilometres. This is thus the corresponding distance for this pair of stores that could be driven in a platoon, lowering the fuel consumption. This process is repeated for all combinations of stores to fill out the entire matrix.

Figure 5: Map showing the included Hoogvliet stores. Source: Hoogvliet.com (2017)
The 40 blue arrows on the map display the 40 stores that are included in the analysis, all located to the west of the distribution centre in Alphen aan den Rijn or inside Alphen aan den Rijn. The distribution centre itself is located at the red arrow. It can be seen that all the stores are located inside the Randstad area.

To supply its stores, Hoogvliet uses some sort of swap body containers that are left at the store by the truck, which picks up the old one that is filled with returnable goods. The swap body containers are cooled and contain the products of all the departments in the supermarket, such as bread, milk, meat and other groceries. As a result, no other external suppliers visit the stores but only the Hoogvliet trucks, which can theoretically depart within five minutes after arrival once the swap body container is swapped. To enable truck platooning, a new driving schedule for the trucks must be made where trucks going in the same direction depart at the same time. This requires information on how many loads each store wishes to receive per day and at what time. Unfortunately, Hoogvliet could or would not cooperate by providing this information, so that an estimation of these numbers had to be made; the only fictive data used in the case analysis. The author has been working at Hoogvliet for over 8 years and managed to learn details about some of the stores. Based on this knowledge, the number of loads for the stores were estimated, where the minimum number of loads is two on a day and the maximum number of loads is five per day, which are realistic values. Table 1 below shows the estimated number of loads per store, including the distance from the distribution centre and the driving time. Not knowing the exact number of loads does not harm the research as it is based on the relative advantage of truck platooning. Using the real number of loads would only make the study more realistic.

Store ID	Total distance (km) from DC	Driving time (hours)	Number of loads	Store ID	Total distance (km) from DC	Driving time (hours)	Number of loads
1	44	0:45	3	**21**	2.4	0:05	2
2	41	0:41	5	**22**	2.9	0:07	5
3	37.6	0:35	3	**23**	1.6	0:03	5
4	33.3	0:34	2	**24**	4.8	0:11	4
5	27.1	0:24	4	**25**	3.1	0:05	2
6	24.7	0:25	3	**26**	16.9	0:22	4
7	27	0:24	4	**27**	14.4	0:19	4
8	34.4	0:36	4	**28**	14.8	0:19	5
9	29.6	0:25	3	**29**	14.6	0:20	4
10	27.9	0:25	4	**30**	18	0:19	3
11	28.2	0:26	3	**31**	19.9	0:28	4
12	23.7	0:23	4	**32**	21	0:30	3
13	23.9	0:25	5	**33**	24.2	0:37	3
14	23.4	0:22	4	**34**	25.4	0:32	5
15	24.5	0:27	2	**35**	24	0:34	3
16	38.4	0:34	3	**36**	20.3	0:27	4
17	22.7	0:26	3	**37**	47.2	0:40	4
18	23.9	0:28	4	**38**	48.6	0:37	3
19	21.2	0:23	5	**39**	44.1	0:37	5
20	18.8	0:24	5	**40**	50	0:40	4

Table 1 Distances, driving times and number of loads per store
The table shows per store what distance must be covered to supply the store from the distribution centre and how long it takes to reach the store. It also shows the number of loads that each store will receive per day. The number of loads is estimated based on the acquired knowledge of the author as Hoogvliet could not cooperate with providing this information.

For each number of loads, fixed times are set for the arrival of the loads. Thus, all stores receiving three loads per day must receive them at the same time. However, a time span of one hour was used in which the load must arrive to allow for some flexibility such that truck platooning can easier be implemented. This flexibility ensures that the departure times of the trucks are not too static but can be varied so that truck platooning is possible.

The fuel consumption of the trucks will play a major role in determining how much can be saved by introducing truck platooning. A report was found about trucks of the brand Volvo, discussing both the emissions and fuel consumption of Volvo trucks over the years (Mårtensson, 2014). It must be noted that this report is published by Volvo itself, but it claims that the values documented in the report are certification measurements and that the values can be used for outlined calculations. For trucks with a Euro 6 engine, it says that the fuel consumption is on average 27,5 litres of diesel per 100 kilometres.

This is for a European tractor and semi-trailer in long-haul traffic. Hoogvliet uses trucks of different brands, including Volvo trucks. Let's assume that Hoogvliet uses trucks with Euro 6 engines, as Hoogvliet has the theme climate in their Corporate Social Responsibility plan. However, Hoogvliet does not use standard trucks with semi-trailers but special trucks that can handle the before mentioned swap body containers. The total weight of the Hoogvliet trucks is therefore probably somewhat lower than a truck with semi-trailer combination. Also, Hoogvliet does not transport over long-haul traffic but over relatively short distances. This increases the fuel consumption to some extent, as less kilometres are driven on highways. To correct for this, the fuel consumption is slightly increased towards 0,3 litres per kilometres. Even though the real fuel consumption could be slightly different, it should not harm the results of the study. It only affects the absolute outcome of the analysis, whereas the unharmed relative outcome will be used instead. The price of one litre diesel is found to be €1,27 at 23 August 2017 for the Netherlands (Dieselprijs.eu, 2017).

3.2 Methodology case study supermarket Hoogvliet

The case study tries to map the network effects of truck platooning by using the distribution traffic of a supermarket. This is done by developing a new driving schedule that minimizes the fuel costs of the trucks. This means that the fuel consumption is minimized, or that the distance covered in a platoon is maximized. This is done via an optimization problem in Excel, where the solver tool is used to minimize the fuel costs. As the problem is too large for the standard solver tool of Excel, the open source software called Open Solver is used, which is developed by Andrew Mason, an academia. This solver is an extension of the standard solver and has more powerful solver engines. It is therefore able to manage larger optimization problems and can solve linear, integer and non-linear problems. The model built in this case study is constructed in such a way that it is linear, ensuring that only one optimal solution exists.

In the model, the day is split into time periods of one quarter each, starting at 05:00 and ending at 18:00 resulting in 53 different time slots, t. During each time slot, trucks may depart to store i in order to supply the store with the required stock. Trucks going to different stores that can depart at the same time and have some distance on the route corresponding may be combined to create a platoon of 2 trucks. To clarify with which ride the truck is combined, the subscript j is introduced that depicts the second store. The ride towards store j is then automatically combined with the ride towards store i and vice versa. Distances covered in a platoon have a 10% lower fuel consumption.

Two matrices form the basis of the model and decide how the trucks are scheduled and combined into platoons. The first matrix is called the allocation matrix and shows for each time slot if a truck departs towards a store. These trucks can either be trucks that are combined with another truck into a platoon or trucks that drive independently. The second matrix consists of 53 loose matrices indicating which rides are combined with each other during each time slot, thus a 40x40 matrix for each quarter of the day. As only platoons of two trucks are considered, trucks can be combined with just one other truck. These two matrices are the variables in the problem and will therefore be adjusted by the solver to find the optimal solution.

The basic model without any restrictions on the number of trucks that are equipped with platooning technology that will be minimalized via Excel is given in formula (1) below. In this formula, the first part resembles the distance covered in a platoon and the second part depicts the distance that must be driven independently.

$$\min P_D\left(\sum_{i=1}^{40}\sum_{j=1}^{40}\sum_{t=1}^{53} b_{ij}^t D_{ij}(1-r)C + \left(\sum_{i=1}^{40} L_i R_i - \sum_{i=1}^{40}\sum_{j=1}^{40}\sum_{t=1}^{53} b_{ij}^t D_{ij}\right)C\right) \quad (1)$$

With some algebra, the model in formula (1) can be simplified into formula (2)

$$\min P_D C\left(\sum_{i=1}^{40} L_i R_i - r\sum_{i=1}^{40}\sum_{j=1}^{40}\sum_{t=1}^{53} b_{ij}^t D_{ij}\right) \quad (2)$$

The model is subject to the constraints:

$$a_i^t \in [0,1] \quad (3)$$

$$b_{ij}^t \in [0,1] \quad (4)$$

$$\sum_{j=1}^{40} b_{ij}^t \leq 1 \quad (5)$$

$$\sum_{i=1}^{40} b_{ij}^t j = \sum_{j}^{40} b_{ij}^t i \quad (6)$$

$$\sum_{j=1}^{40} b_{ij}^t \leq a_i^t \quad (7)$$

$$a_i^t + a_i^{t+1} + a_i^{t+2} + a_i^{t+3} \leq 1 \quad (8)$$

$$a_i^t \leq Q_i^t \quad (9)$$

$$t_{ik}^{min} \leq t_{ik} \leq t_{ik}^{max} \quad (10)$$

$$\sum_{t=1}^{53} a_i^t = L_i \quad (11)$$

$$\left(\sum_{i=1}^{40} L_i R_i - \sum_{i=1}^{40}\sum_{j=1}^{40}\sum_{t=1}^{53} b_{ij}^t D_{ij}\right) + \sum_{i=1}^{40}\sum_{j=1}^{40}\sum_{t=1}^{53} b_{ij}^t D_{ij} = \sum_{i=1}^{40} L_i R_i \quad (12)$$

With the model parameters defined as:

P_D Price of one litre diesel, set at 1,27

b_{ij}^t Binary variable indicating whether a truck heading towards store *i* forms a platoon with a truck heading towards store *j*, departing at time *t*

D_{ij} Corresponding distance on route for stores *i* and *j*

L_i Number of loads that store *i* receives per day

R_i Total length of the route between the distribution centre and store *i*

a_i^t Binary variable displaying whether a truck departs towards store *i* at time *t*

Q_i^t Binary variable displaying whether a truck may depart to store *i* at time at time *t* in order to arrive within the pre-set time period

t_{ik}^{min} Earliest time at which a truck can depart to store *i* for load *k* to arrive within the desired span

t_{ik} Time at which a truck departs to store *i* for load *k*
t_{ik}^{max} Latest time at which a truck can depart to store *i* for load *k* to arrive within the desired span
r Reduction in fuel costs when driving in a platoon, set at 10%
C Fuel consumption in litres/km

Constraints (3) and (4) guarantee that the allocated loads per store and time slot are binary. Constraints (5) and (6) guarantee that only one combination can be made per truck and that if store *i* is combined with store *j*, the combination is the same the other way around. (7) guarantees that the number of trucks leaving to platoon at a certain time slot does not exceed the number of trucks that depart in reality. Constraints (8) and (9) ensure that not all trucks for one store depart at the same time (within one hour) and that each truck departs in time in order for the stock to arrive in time. (10) ensures that the trucks depart within the set time span so that the load arrives at the store within the desired time span. (11) Ensures that the number of trucks departing to each store equals the number of loads that the store must receive. Finally, constraint (12) ensures that the total distance that is driven equals the distances that must be driven. By definition, this constraint always holds but is necessary for the model to work properly. The model in Excel yields a total of 89.040 variable cells and 178 solver constraints.

Some assumptions are necessary for the model to work and to reduce the size and complexity of the problem, simplifying the model slightly compared to reality. Firstly, the model only considers the journey from the distribution centre towards the stores and ignores all the retour journeys. These retour journeys also have potential possibilities for truck platooning but this requires that the trucks meet up somewhere during the ride, something that will mainly happen by coincidence. Second, the model is made for one specific day only. By simply modifying the input data, the model can generate the optimal outcome for every day. However, for the study, it is assumed that every day is the same and follows the schedule that is created here. Sundays are however significantly different from the other days of the week. Because of this, and to correct for the possibility of national holidays, it is assumed that the generated schedule will be used for 300 days per year. While in reality one should take into account capacity, this model ignores any form of capacity constraints. It is assumed that there are always enough trucks and drivers available. There is also no capacity constraint for the distribution centre such that it can always handle all the outward going trucks in time. With regards to driving, the model ignores the possibility of congestion. It also assumes a fixed fuel consumption per kilometre, independent of driving conditions and the cargo transported. The 10% decrease in fuel consumption while driving in a platoon is fixed for both the leading and following truck, as was discussed in section 2.2. It is assumed that every single metre driven in a platoon leads to a 10% reduction in fuel consumption. Finally, it is assumed that the price of diesel remains constant over time.

For the first hypothesis, it is required that the maximum number of trucks equipped with platooning technology that are on the way at a time can be varied. To do so, the number of platooning trucks on the way at a certain time must be calculated first. This is done via multiple help matrices which are binary and 1 if a truck is platooning and 0 otherwise. For the platooning trucks, it is calculated how long it will take for the truck to return, which is set equal to twice the driving time plus fifteen minutes for swapping the container at the store. It is then known how long that truck cannot be used for other rides. Summing up all the trucks per time period *t* shows how many trucks with platooning technology are on the way for each time period *t*. An additional constraint is added to the model which limits the maximum number of trucks that can be used with platooning technology installed on them. This constraint is given in (12). As platooning happens in pairs, the maximum number of trucks with platooning technology is increased in steps of two after which the model is resolved.

$$\sum_{i=1}^{40} p_i^t \leq p^m \quad for\ each\ period\ t \tag{12}$$

With

p_i^t Binary variable indicating whether a truck with platooning technology is on the way for store *i* at time *t*

p^m Manually adjusted integer showing the maximum number of trucks allowed on the way that have platooning technology installed

For the second hypothesis, the distances between the DC and the stores as well as the corresponding distances on the different routes are adjusted. This is done by multiplying all the different distances with the same factor, X. X Can for example be set at 10, such that the distances are multiplied with a factor 10. It can then be observed what the effect of distance is on the benefits of truck platooning. To enable a good comparison compared to the status quo, the driving times are held constant so that the driving scheme remains the same. This is of course unrealistic but is solely done for the purpose of a good comparison. In addition, an analysis will be performed where only the distances that can be driven in a platoon are multiplied by the distance multiplication factor, while the distances that remain to be driven individually are kept constant.

3.3 Costs of implementation

To determine whether truck platooning is attractive for Hoogvliet and results in a net saving, the cost of implementing truck platooning must be subtracted from the annual savings in fuel costs. Only if the benefits exceed the costs, it can be concluded that truck platooning is beneficial. Therefore, it is required that the costs of implementation are listed. For these costs, the report written by Janssen et al. (2015) will be used. The authors of this report state that currently the costs of equipping a truck with the required technology are about €10.000 per truck. This includes the vehicle to vehicle communication, communication with the driver and other additional safety measures that are necessary. However, they claim that in the future the costs of installing this technology will decrease to €2.000 per truck. Furthermore, the authors assume a depreciation period of seven years in which the truck and the technology will be depreciated such that the annual cost of the technology is €286.

According to Janssen et al. (2015), the trucks employed with platooning technology will need additional periodic testing and maintenance. Especially the brakes need additional checks, twice a year instead of the usual once a year. The costs for this are by the authors estimated to be €150 per year. Furthermore, drivers will need extra training to obtain a license that allows them to drive in a platoon. Based on the before mentioned LZV vehicles and the SARTRE project, the authors of the report estimate that the cost of the training will be €1.500. The license lasts for about twenty years on average, according to the authors, such that the annual cost of the license is €75. During this research, it will be assumed that there is only one driver per truck, to make calculations and comparisons possible. Summing up all the costs results in annual costs of €511 per truck. In these costs, the fee for the platooning service provider discussed in section 2.2 is ignored, while Janssen and colleagues estimate the fee to be €150 per year. The service provider will not be considered in this research and this cost is therefore irrelevant.

4. Results

For a good comparison, it must be known how much fuel is consumed to supply all the stores without truck platooning. This requires calculating the total distance that is covered by all the trucks on each route, multiplied by the number of loads that each store receives. This simple calculation reveals that per day 3680,1 kilometres must be driven. With a fuel consumption of 0,3 litres per kilometre, a total of 1104 litres of diesel is used which costs €1402,2 per day at a price of €1,27 per litre diesel. Using the assumption that the schedule created in this case analysis is used for 300 days per year, the annual figures are calculated. As a result, 1.104.030 kilometres per year are driven, with an annual fuel consumption of 331.209 litres of diesel that costs €420.635,43 per annum. It is the annual fuel cost that will be used in the remainder of this analysis, against which it is compared how much savings truck platooning yields.

4.1 Network effects

To inspect whether network effects are present for truck platooning and if so, how large these network effects are, only the reduction in fuel consumption and fuel costs are used that truck platooning provide. The investment costs are thus ignored, as these costs automatically increase when the number of trucks equipped with platooning technology is increased. The number of trucks that are equipped with truck platooning is increased in steps of two, after which the optimal schedule is regenerated via the Excel solver. This procedure allows to visualize how the benefits of truck platooning develop with the number of platooning trucks.

Figure 6 shows a graph that plots the number of trucks that are equipped with platooning technology against the fraction of kilometres driven in a platoon and the annualized fuel costs. The left vertical axis shows what percentage of the total distance that must be covered is driven in a platoon, while the number of platooning trucks is increased. It is clearly visible, as one can expect, that the distance covered in a platoon increases with the number of platooning trucks. When only few trucks are equipped with the technology, the model dedicates the platooning trucks on the routes that have the largest corresponding distances. Therefore, the graph is relatively steep in the beginning. As the number of trucks equipped with the technology increases, the less attractive routes are also scheduled with platooning trucks. As a result, the curve flattens for higher numbers of platooning trucks. Based on the graph in figure 6, it can be said that the effect of increasing the number of platooning trucks results in decreasing economies of scale w.r.t. the fraction of kilometres driven in a platoon.

At the same time and following from the distance that is driven in a platoon, the annualized fuel costs decrease with the number of trucks that are equipped with platooning technology. When not a single truck is platooning, no fuel is saved and consequently there is no saving in fuel costs. When the number of platooning trucks is increased, leading to more distance being driven in a platoon, the saving in fuel costs starts to increase. As was the case with the fraction of the distance driven in a platoon, the slope of the fuel costs curve is rather steep at the beginning and flattens as more trucks are equipped with the technology. Again, there are thus decreasing economies of scale visible. That the two curves have the same but reversed pattern is logical as the two figures are perfectly related. After all, truck platooning reduces the fuel consumption by 10%, thus the more is platooned, the more is saved on fuel costs.

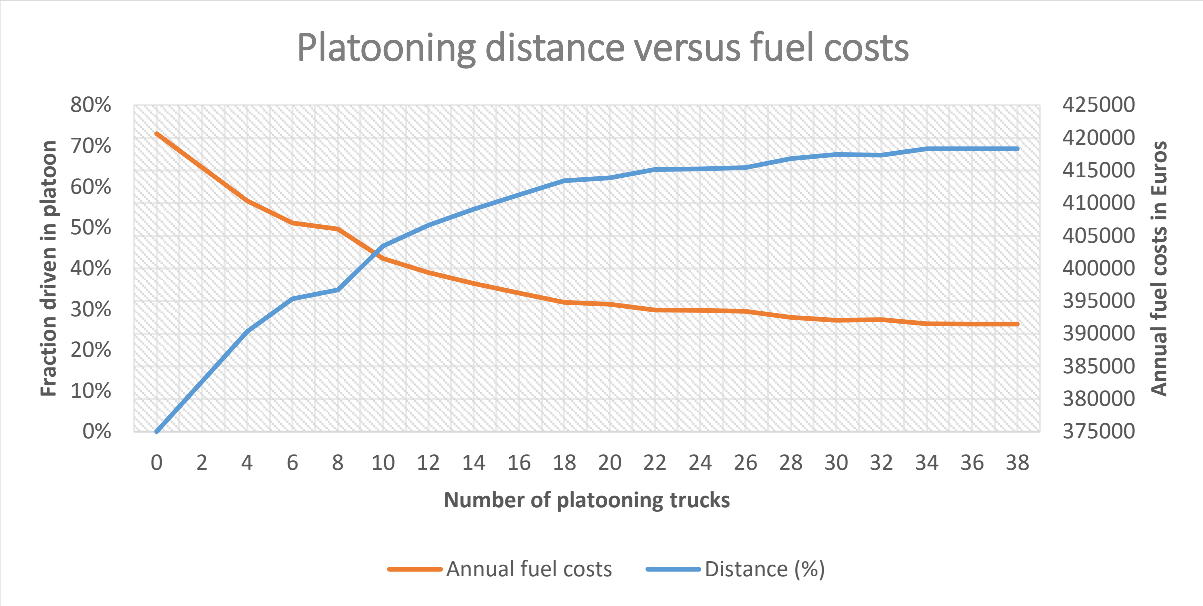

Figure 6: Effect of number of platooning trucks on platooned distance and fuel costs

This graph shows how the fraction of the total distance covered in a platoon (left axis) and the annualized fuel costs (right axis) develop with the number of trucks that are equipped with platooning technology. As one can expect, the total distance covered in a platoon increases as more trucks are equipped with the technology. At the same time, related with this fraction, the fuel costs decrease when more trucks are equipped with the technology. Both curves show decreasing economies of scale, as first the most beneficial routes are gratified, followed by the routes with lower corresponding distances if the platooning capacity increases. Clearly visible is how network effects are present, with both variables developing profitable as the number of platooning trucks increases.

The blue line in figure 7 shows the annualized saving in fuel costs as a fraction of the total fuel costs that would be incurred without truck platooning, just like it is today. The graph reveals how the relative saving increases with the number of trucks equipped with platooning technology. Logically, the graph has the same shape as the fraction of kilometres driven in a platoon. More specifically, the fraction of kilometres driven in a platoon is ten times the percentage of the annualized reduction in fuel costs. This makes sense, as platooning leads to a 10% reduction in fuel consumption. Employing truck platooning can save up to 6,9% in total fuel costs when 38 trucks are equipped with platooning technology. The same reduction in fuel costs can be obtained while 34 trucks are equipped with the technology, avoiding some investment costs. Table A2 in the appendix gives a complete overview showing all the obtained results and figures per number of platooning trucks in detail.

Figure 7 also shows the marginal reduction in fuel costs, illustrated by the orange line. Theoretically, this line should never be negative as the same schedule can always be generated as was done with less trucks, by not using the additional trucks with platooning technology as platooning trucks. The savings should thus be at least the same or higher. In the graph, the decreasing economies of scale is again visible. With few platooning trucks, the marginal reductions are rather large at 1,2% while this deceases to values around 0,5% for ten to eighteen trucks employed with truck platooning. For higher numbers of trucks equipped with the technology, the marginal reduction reduces further to values close to zero. Still, the marginal reductions are positive at all times, providing evidence that network effects are present. After all, increasing the number of platooning trucks remains reducing the annualized fuel costs, albeit by a lower amount.

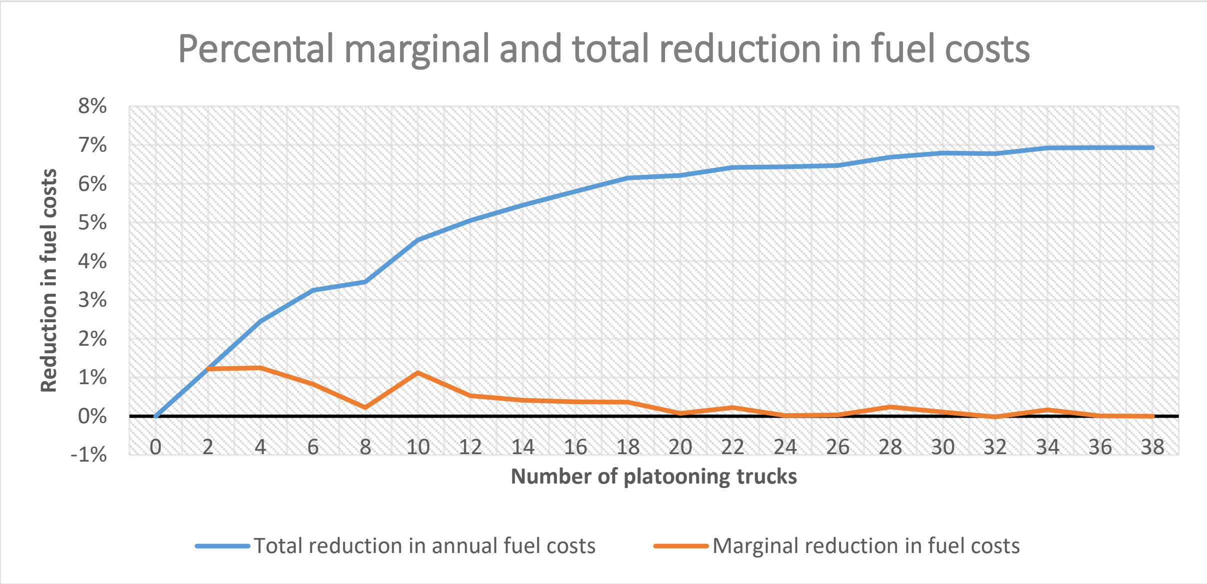

Figure 7: Annualized fuel savings
This graph shows how the annual fuel savings relate with the number of platooning trucks as a share of the total fuel costs that must are incurred without truck platooning. It can be seen that the relative annual fuel savings increase with the number of platooning trucks. At the higher number of platooning trucks, 6,9% can be saved on the total fuel costs. The graph also displays how the marginal reduction in fuel costs develop with the number of platooning trucks. This value is relatively high for low values of platooning trucks, but decreases as the number of platooning trucks is increased. Still the marginal reduction is always positive, providing evidence for network effects to be present.

Figure 8 shows the total annualized reduction in fuel costs divided by the number of platooning trucks. The decreasing orange line illustrates how the first platooning trucks are used most efficiently, leading to the largest reduction in fuel costs per truck. As the number of platooning trucks increases, the reduction in fuel costs per truck decreases, to reach the lowest value of €715 reduction in fuel costs per truck at 36 platooning trucks. Still, this is higher than the investment costs of €511, meaning that it is beneficial to employ truck platooning. This observation complements the graphs above, indicating that network effects are present. Figure 8 also shows, in blue, how the total fuel costs divided by the total number of required trucks differs for different number of platooning trucks. Here, the number of trucks includes both the platooning trucks and the trucks that drive independently. Although the fuel costs per truck are rather variable, the dashed linear trendline indicates that the total fuel costs per truck decrease as the number platooning trucks increases. This observation suggests that employing truck platooning is still beneficial when considering the entire truck fleet and not just the platooning trucks.

What becomes clear from figures 6 and 7 is that truck platooning does carry network effects. The savings increase as the number of platooning trucks increase. The marginal network effects are large for low numbers of trucks with platooning technology and decrease as the number of trucks with platooning technology increase. This is further illustrated in figure 8. Still, the network effects can best be exploited for high numbers of platooning trucks, maximizing the total distance that can be covered in a platoon. Maximizing this distance also maximizes the reduction in fuel consumption and costs. Figure 8 shows that considering the entire truck fleet, truck platooning leads to lower average fuel costs per truck. The more trucks are equipped with platooning technology, the lower the fuel costs. Therefore, the first hypothesis cannot be rejected and it is assumed that truck platooning holds network effects.

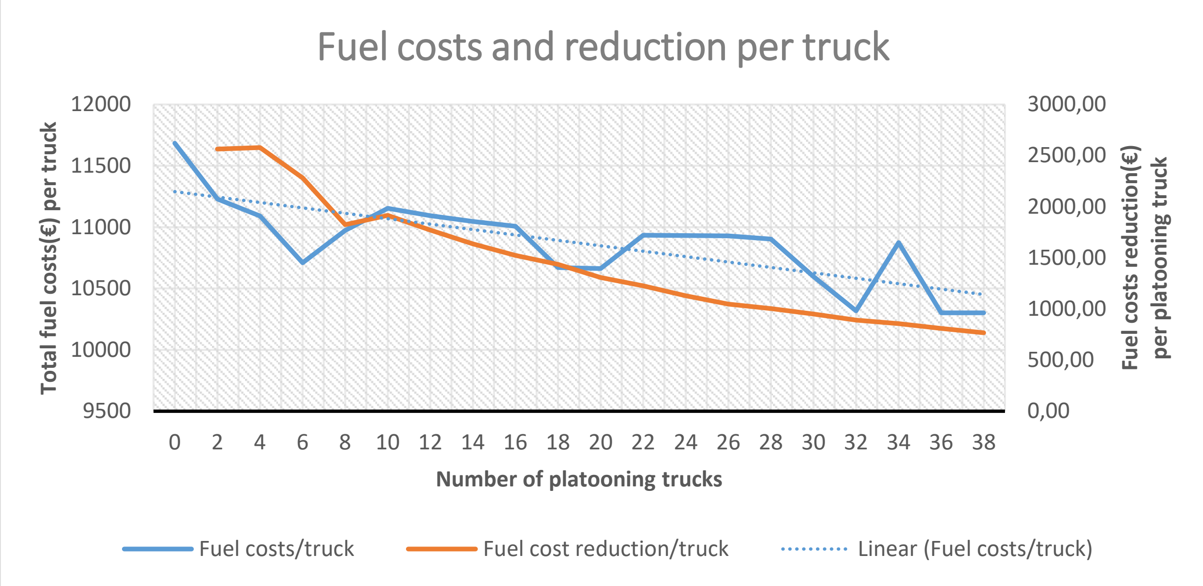

Figure 8: Total fuel costs per truck and reduction in fuel costs per platooning truck
This graph shows in orange (right axis) how the total annual reduction in fuel costs divided by the number of platooning trucks evolves with the number of platooning trucks. A negative slope is clearly visible, indicating that increasing the number of platooning trucks results in a lower reduction in fuel costs per truck. Decreasing economies of scale are thus present. Still, at the lowest point, the reduction in fuel costs per truck is higher than the investment costs of €511 per truck, showing that truck platooning is beneficial. In blue (left axis), it is shown how the total fuel costs divided by the total number of required trucks (both platooning and not platooning) develop as the number of platooning trucks increase. The dashed trendline shows that for the entire fleet, the average fuel costs decrease as more trucks are equipped with platooning technology.

4.2 Increased distances

To find out how the distances of the routes influence the reduction in fuel consumption that results from truck platooning, the constraint on the maximum number of platooning trucks is removed, done by setting the number at 40. The model is resolved using various factors with which the distances are multiplied. In the base model, the distances are multiplied with a factor 1, resulting in the normal and real distances. The other factors that are considered are 2, 3, 5, 10, 15. For factors higher than 15, the distances of the routes become too large to remain meaningful with a schedule as is generated in this study. The driving times and other parameters are unchanged to allow the formation of the same schedule. As the focus is still on the reductions in fuel consumption and costs, the investment costs are ignored in this analysis.

The graph in figure 9 shows how the percentage of the distance that is driven in a platoon develops when the distance factor is increased. The fraction of platooned kilometres remains approximately constant at values between 67,7% and 69,1%. This observation makes sense since the ratio of distances that can be platooned and must be driven independently remains constant as both parts are multiplied with the same factor. In the graph, it looks like the percentage is varying rather much, but this is due to the scale of the vertical axis.

Figure 9 also shows how the annual fuel costs divided by the distance multiplication factor evolves with the distance factor. The resulting graph is the exact reflection of the fraction driven in a platoon. As a result, this value is also relatively constant at values between €391.500 and €392.200 per factor of distance. This tells us that the relative benefits of platooning are approximately constant with the distance that the trucks must cover. The other way around, if the annual fuel costs per distance factor

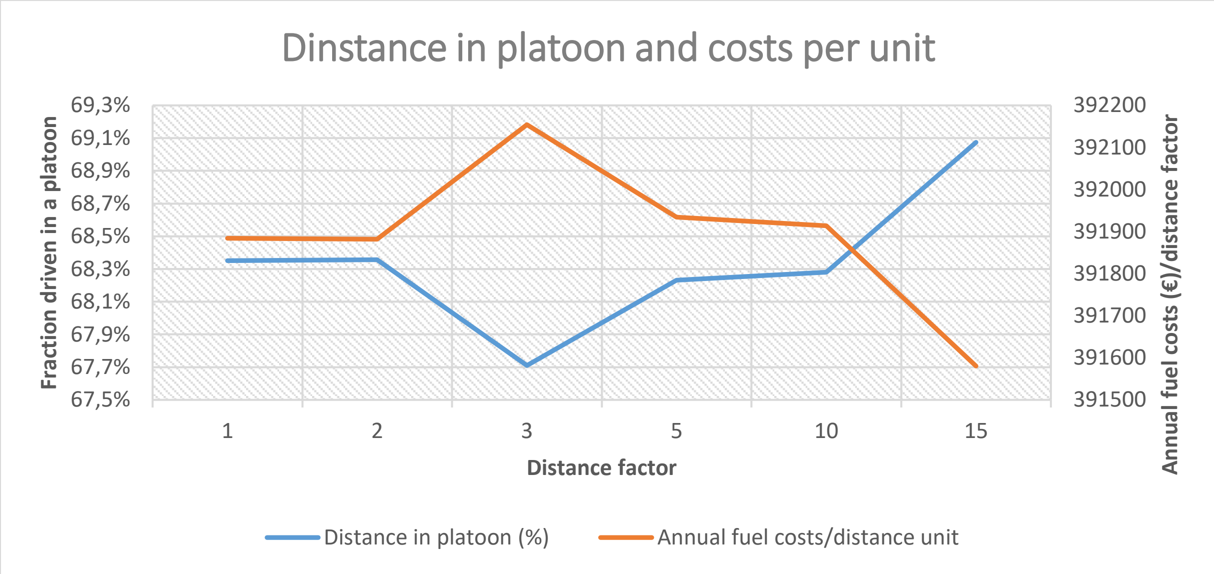

Figure 9: Distance driven in platoon for different distance factors and fuel costs per distance factor
The graph shows what fraction of the total distance that must be covered is driven in a platoon. This is shown by the blue line (left axis). It can be seen that a relative stable fraction of the total distance is driven in a platoon, which makes sense as both the total routes and the distance that can be platooned are multiplied with the same factor. The orange line (right axis) shows the total annual fuel costs divided by the distance factor. This figure is a reflection of the orange line and also relatively stable. This indicates that, for this particular case, increasing the length of the route does not increase the benefits of truck platooning.

are divided by the annual fuel costs of the case where the distance factor is set at 1, the outcome is equal to the corresponding distance factor for every instance. Thus, for distance factor 10, the annual fuel costs are exactly ten times the annual fuel costs found for distance factor 1. This says that the benefits that result from truck platooning do not grow with the length of the routes, at least not in this set up of the case study.

From figure 9, the percental annual saving of fuel costs can simply be derived. Because the two factors are perfectly correlated, the shape of the curve is exactly the same as the fraction driven in a platoon, but the percentages are ten times smaller. Thus, the annual saving in fuel costs is approximately constant between 6,8% to 6,9%. This too adds to the observation that increasing the distance of the routes, does not add to the benefits of truck platooning. This is probably due to the fact that the driving times and such are kept constant. As a result, approximately the same schedule is made for each case. The schedules differ on some minor points, where mainly the trucks for the first load depart at different times and are combined with other trucks in the different cases. Therefore, the annual fuel saving is not perfectly constant but varies slightly. Table A3 in the appendix lists all the exact outcomes and results.

However, it seems unrealistic that the saving in fuel consumption does not increase with the total distance of the routes. Usually on longer routes, more distance is driven on highways (Dye, n.d.). This may affect the average fuel consumption as the trucks are able to constantly drive at an optimal speed without being hindered by traffic lights. As the trucks used in this case study cover relative short distances, the trucks will probably face relatively many traffic lights. This results in much breaking and pulling up, increasing the fuel consumption of the truck. The type of cargo transported may also be different for long haulage transportation, as well as the characteristics of the trucks. These are some factors that can influence the fuel consumption, that are outside the scope of this model. But changing the fuel consumption per kilometre does not influence the relative reduction in fuel consumption, only the absolute savings. After all, the ratio between the platooned and independently driven kilometres remain constant. As the platooned kilometres give a 10% reduction in fuel consumption, the total percental saving in fuel cost will remain the same for every value of fuel consumption.

More important is probably the fact that for long haulage transportation, a larger share of the route can be driven in a platoon, on the beforementioned highways. Only the last few kilometres towards the destination are then required to be driven independently. It is then plausible that the ratio of kilometres driven in- and outside a platoon changes, with a larger fraction driven inside a platoon. As the other parameters are fixed in the model, this option is the only option that can be investigated via the model.

This last idea can be executed by setting the kilometres that must be driven independently, i.e. the last kilometres, at fixed values. They are thus not multiplied by the distance factor that was used before. As the total length of the routes increase substantially, the initial total length of the routes are used for this value. The independently driven kilometres are then equal to the sum of the number of loads multiplied by the length of the routes; in total 3680,1 kilometres. The kilometres that can be driven in a platoon are, however, still multiplied by the distance factor. The result is that the total distance of the routes increase, where the distance that can be platooned increases as the distance factor is increased, while the independently driven kilometres remain constant. The total distance is here set at the sum of the number of kilometres driven in and out of a platoon. This procedure leads to a change in the ratio of kilometres driven in a platoon and kilometres driven independently.

Figure 10 below shows how the graph in figure 9 changes when this new methodology is applied on the model. The blue line again displays the fraction of kilometres driven in a platoon. This fraction clearly increases as the distance factor is increased, starting at 40,6% for a factor of 1, increasing towards 91,1% for a factor of 15. The percental annual reduction in fuel costs can again by derived from this curve, by dividing the percentages on the left axis by 10. This results in reductions in fuel costs of 4% up to 9,1% for factors 1 and 15, respectively. This is much higher than the 6,9% reduction that was achieved earlier, when both distances are multiplied with the same factor. By allowing the ratio to change, truck platooning does seem to provide increasing benefits for larger distances, a remarkable and useful result. Table A4 in the appendix shows the exact numbers.

This latter observation is confirmed by the orange line in figure 10, which again displays the annualized fuel costs divided by the distance factor. This value decreases significantly as the distance factor is increased. At distance factor 1, this value is €679.394, much higher than it was in the earlier case. But for a distance factor of 15, the value has decreased to €286.801, nearly two and a half times as low. The fuel costs are no longer increased by the same factor as the distance, but by a lower amount. When the distance is multiplied with 10, the fuel costs are only 4,4 times as high than the case of distance factor 1. If the distances are multiplied by 15, the fuel costs increase by a factor of 6,3. The multiplication factor is then increased with 5, while the factor with which the costs increase goes up by only 1,9. This too reveals that, when the ratio of kilometres is allowed to vary, the benefits of truck platooning increase with the distance of the routes.

The two simple analyses performed in this section give different, contradicting results. In the first instance, where both the distances that are platooned and driven independently are multiplied by a distance factor, truck platooning does not show increased benefits for higher distances. In the second instance, when the ratio is allowed to vary, this positive relationship is found though. Although the methodology of both models is very rough, both being harmed by some very simplifying assumptions, it seems that the second option is more realistic. It is likely that for longer rides, a higher fraction of the route can be driven in a platoon as usually most of the journey is driven on highways. Only the first

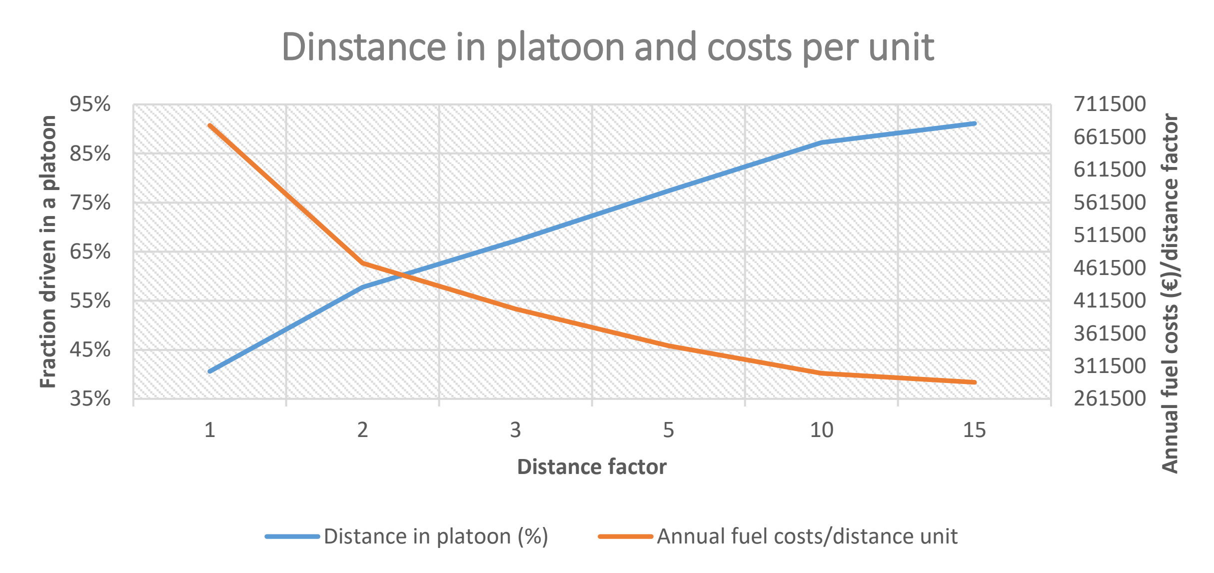

Figure 10: Annual percental fuel saving for different distances

The graph shows in blue what fraction is driven in a platoon (left axis) and in orange the fuel costs divided by the distance factor (right axis). In deriving this graph, only the platooned distances are multiplied by the distance factor, whereas the kilometres driven independently are set at a fixed value. It is visible how the fraction of kilometres driven in a platoon increases with the distance factor. This is due to the fact that more kilometres are driven on highways, resulting in more platooning opportunities. With a larger share driven in a platoon, the annual fuel costs per distance factor decrease impressively. This suggest that there is a positive relationship between platooning kilometres and the reduction in fuel costs.

and last few kilometres need to be driven on local roads, where the opportunities of driving in a platoon may be limited. It is then logical that the percentage of the route that can (and probably will) be driven in a platoon is higher for long haul transportation. This leads to higher relative reductions in fuel consumption and fuel costs. Therefore, the second model, displayed in figure 10, is considered to be the most realistic version. Following the results from this model, the second hypothesis claiming a positive relationship between platooning distance and fuel reductions cannot be rejected.

4.3 Net savings

Thus far, the investment costs of installing the platooning technology onto the trucks have been ignored. But since truck platooning does not come for free, it is relevant to include these cost into the analysis. As was elaborated in the literature review, the first users of truck platooning may find it challenging to harvest the benefits that the technology can provide. This is true because they have no guarantee that their reduction in fuel costs exceeds the investment costs. Therefore, to investigate to what extent truck platooning really is attractive, the investment costs need to be taken into consideration which equals, as is given in section 3.3, €511 per truck equipped with truck platooning.

Figure 8 showed how the reduction in fuel costs per truck decrease as the number of trucks equipped with truck platooning technology increases. This decreasing trend is confirmed by figure 7, showing the percental marginal reduction in fuel costs when additional trucks are equipped with the technology. Logically, a firm would only invest an additional €511 per year on installing the technology on an extra truck if this results in a reduction in fuel costs larger than €511 per year. In the context of this case study, this may mean that at a certain point if more trucks are equipped with the technology, not enough distance can be driven in a platoon to ensure that this condition is met. It is then cheaper to drive alone, avoiding the investment costs.

Using the results of the first hypothesis, it is easy to subtract the investment costs from the reduction in fuel costs. Here, the investment costs equal the number of trucks that are allowed to drive in a platoon multiplied by the annual additional cost of employing a truck with truck platooning, set at €511. Figure 11 below shows how the annual net savings develop with the number of trucks that have platooning technology installed. Here, the blue line shows how much can be saved annually in euro's whereas the orange line depicts the percental savings per annum, compared to the status quo without truck platooning. Only the fuel and investment costs are considered for the status quo whereas the investment costs only capture the platooning related costs. Both curves are identical and have the same shape, but to make both lines visible, the maximum values of the vertical axes are set slightly different. Table A5 in the appendix shows a full overview of the annual net savings.

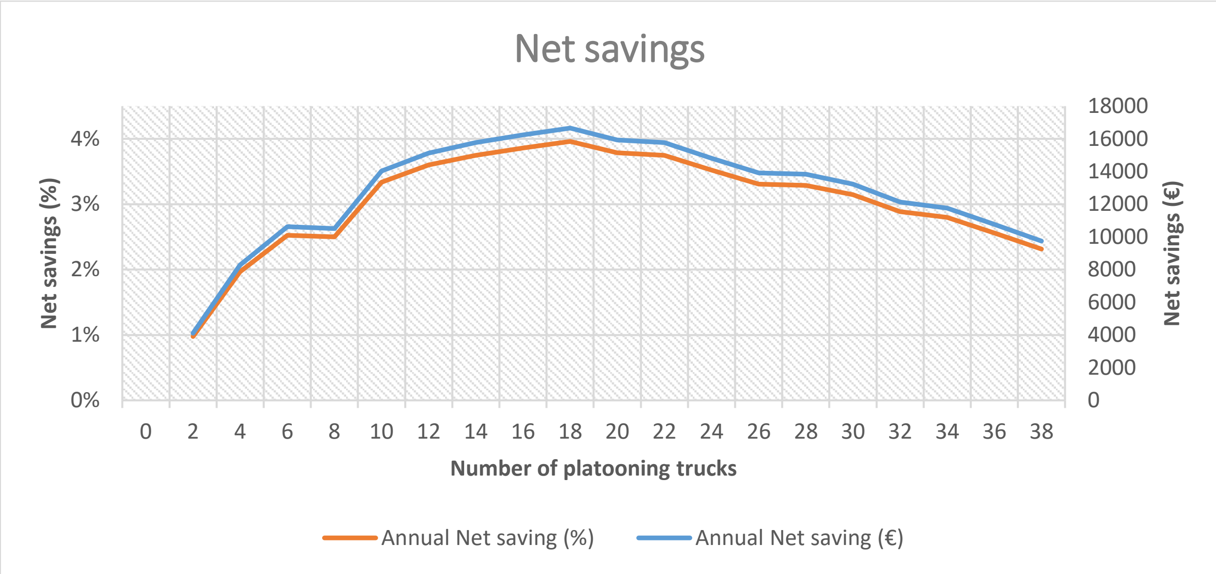

Figure 11: Net savings
The graph shows how much can be saved by employing truck platooning, net of investment costs. In orange (left axis) the percental savings are shown, whereas in blue (right axis) the absolute savings are shown, both compared to the status quo without truck platooning. The curve shows a parabolic concave shape, indicating that there is an optimal number of trucks that can be used for truck platooning. Beyond this point, the investment costs of equipping another truck with the technology outweighs the additional reduction in fuel saving that this truck provides.

It can be seen that the curve has a parabolic concave shape. The top lies at eighteen trucks employed with truck platooning. Equipping more trucks with the technology, deteriorates the annual net savings as the investment costs outweigh the additional reduction in fuel costs. In the most cost-efficient case, with eighteen platooning trucks, €16.657 can be saved annually. This equals a reduction of 4,0% compared to the status quo. Clearly, truck platooning provides positive benefits for the supermarket considered in this case. Even though a reduction of 4,0% is not impressive, in the fight between supermarkets to offer its customers the lowest prices, this reduction in logistic costs may help.

To elaborate on this idea, Hoogvliet recently announced that it signed a contract for a new state of the art distribution centre (Hallema, 2017). The new DC is an important factor in Hoogvliet's strategy to be the most attractive supermarket in its market area. They claim that, in order to keep their prices as low as possible, the aim is to minimalize the costs of distribution and logistics. The new DC helps in doing so, but as shown above, truck platooning may also help reduce the costs of distribution and logistics.

Based on this simple analysis, it seems safe to state that supermarkets fulfil the characteristics of being potential first users of truck platooning. They operate a sufficient number of trucks to be able to reap the harvest of truck platooning without having to rely on external parties. Furthermore, supermarkets can bear the investments costs as they are likely to generate enough savings in fuel costs to earn the costs of instalment back. There is however, as shown in figure 11, a limit to the number of trucks that should have platooning technology installed. In this case, only eighteen trucks should be equipped with the technology, whereas with this number of platooning trucks a total of 37 trucks is required to supply all the stores in time. Apparently, only a selection of stores is attractive to supply by platooning trucks (the stores that are located further away from the DC but close to other stores, while other stores do not generate enough reductions in fuel costs to validate the investment costs (stores located close to the DC or far from other stores).

There are of course other firms that operate multiple trucks on corresponding routes. These firms have not been investigated here, but could also be suitable or even better candidates for first adopters of truck platooning. But supermarkets are rather unique in that they operate via a fixed schedule, facilitating the use of truck platooning. That the trucks cover relative short distances is apparently not a limitation, but based on figure 11 it seems plausible that there is a minimum distance of a route after which truck platooning becomes beneficial. According to figures 9 and 10 the total length of the routes is unimportant, but it is the ratio of kilometres driven in a platoon versus kilometres driven outside a platoon that is decisive on how attractive truck platooning is. The case showed that supermarkets do have routes with high enough ratios, enabling positive results.

4.4 Evaluation of the results

The pattern observed in section 4.1 corresponds with the results found via simulations by Van de Hoef, Johansson and Dimarogonas (2015), shown in figure 12. The authors used various Monte Carlo simulations where they mapped the reduction in fuel costs from platooning by increasing the number of trucks that can platoon, while aiming to create fuel-optimal speed profiles. The authors used very high number of trucks, up to 7000, to estimate the resulting benefits. The pattern found in the case study here resembles the pattern found by van de Hoef et al. for spontaneous platooning, where the marginal reduction in fuel consumption is somewhat higher for lower number of trucks. At the highest value of 7000 platooning trucks, fuel reductions of about 6% are obtained, while an asymptote of around 7% seems to be present. For pairwise generated platoons, the authors find the curve depicting the reductions in fuel consumption to be very steep for up to 1000 platooning trucks, to remain nearly constant beyond 1000 trucks at 6%. The authors note that the relative fuel savings are upper bounded by 10%, the reduction in fuel consumption that platooning maximally provides. To achieve this value, each truck should be a following truck, driving in a platoon during the entire journey. The authors conclude that coordinating the process of platooning is essential for small numbers of trucks, and that this coordination can lead to way higher savings in fuel consumption than spontaneous platooning.

Comparing the results of this case study and the simulations from van de Hoef et al. (2015) reveals that the realistically achievable reduction in fuel consumption lies somewhere between 6% and 7%. That this reduction can be obtained with relatively few trucks in this case study compared to van de Hoef et al. is probably explained by the fact that in this case study, all trucks are operated by the same firm, departing from the same location and driving via a fixed schedule. In the simulation by van de Hoef et al. The trucks are operated by multiple independent firms, departing and heading to many different locations. There is in this case a smaller chance to 'match' with another truck, demanding more trucks to create a match. This case study adds to existing literature by showing that the benefits of truck platooning can also be achieved with fewer truck, if the trucks are well coordinated and operate within a selected area.

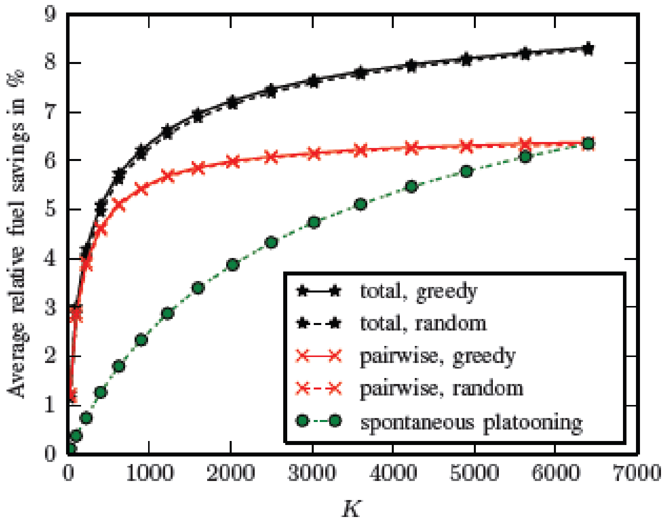

Figure 12: Results from simulation models by van de Hoef et al. Source: copied from *(van de Hoef et al. 2015)*
The figure shows the results from the simulations performed by van de Hoef and colleagues (2015). The average relative fuel savings are plotted against the number of trucks, K. It can be observed that the curve found for spontaneous platooning is the same as the curve found in section 4.1. The pairwise generated platoons lead to very high reductions in fuel consumptions for relatively few trucks. Notable is that the maximum realistically obtainable reduction in fuel consumption found in these simulations corresponds with the values found in this case study, at about 6-7%.

The effect of the length of the routes on the benefits of truck platooning is not extensively investigated on its own, but is a point of interest in several researches. In his thesis, Bakermans (2016) mapped the percental normalized fuel benefits for different numbers of truck flows per hour over increasing trip distances. Logically, the benefit is larger for higher densities as this allows an easier formation of a platoon. Bakermans also found that the benefits increase somewhat for longer trip distances, but that after a certain distance the benefits flattens and remains stable. For a high density of 120 truck per hour, only short distances are required to provide benefits and for distances past 20 kilometres not much additional reductions are gained. For lower truck flow densities, the distances of the trips must be somewhat larger for truck platooning to be beneficial, but at a density of 30 trucks per hour, 20 kilometres is still sufficient. In this latter case, the benefits increase most for trips up to 50 kilometres, after which the benefits stabilize. After a certain point, the length of the trips is thus unimportant for the percental benefits that truck platooning can provide and the reduction in fuel consumption remains constant. This corresponds with the observation made in this case study, as figure 9 shows.

Liang, Martensson and Johansson (2013) tried to determine a ratio for which truck platooning becomes attractive. The authors did not use the ratio of the kilometres driven inside and outside a platoon, but focussed on the gap that the following truck must close when it wants to form a platoon with another truck that drives ahead. While their ratio focusses on some technical aspects, including air drag and resistance, increased fuel consumption of driving at higher speeds to close the gap and such, they also use the ratio between the distance that can be driven in a platoon once the gap is closed and the distance of the initial gap. If this ratio is too low, i.e. too little can be driven in a platoon or too much must be driven individually to cover the gap, platooning is unattractive and the following vehicle can better keep driving alone. The ratio has a breakeven point where platooning starts to become beneficial, but the exact value of this ratio depends on the technical aspects of the truck. As the ratio increases, so do the benefits of truck platooning, the authors show. This observation is in line with the present case study, as can be seen in figure 10. Here too, a higher ratio between kilometres driven in a platoon and kilometres driven independently leads to higher benefits. It seems therefore viable to state that it is not the length of the trips but the ratio of the kilometres that determine how beneficial truck platooning is.

5. Conclusion

The motivation for performing the research in this thesis was the deteriorated profitability of trucking firms during the last decade, partly due to the global financial downturn. Lowering the costs of transportation is important in solving this problem. The invention of truck platooning was raised as a possible solution that may help in doing so. With truck platooning, trucks drive very close to each other while being connected via advanced Wi-Fi connections, limiting the air resistance. This reduction of air resistance leads to a lower fuel consumption of the trucks, where up to 10% can be saved on fuel costs for the entire platoon. The problem that arose with this technology is that the first users of truck platooning may find it challenging to fully exploit the benefits of truck platooning, while being faced with the costs of installing and using the technology. Only large firms with multiple trucks operational on the same route can reap the harvest of truck platooning, without having to rely on other parties.

A solution for this problem is to make the platooning technology of trucks of different brands compatible with each other, such that truck drivers can form platoons on-the-go with 'strangers'. The idea is that the more trucks on the road are equipped with platooning technology, the easier it gets for form a platoon and the more can be saved on fuel costs. This resembles the theory of network effects, where the utility that one derives from using a good increases with the number of users of that good. Via a case study, it was investigated in this thesis whether truck platooning holds network effects. It was found that this is the case, where the total benefits of all platooning trucks are considered together. Focusing on reductions in fuel consumption and fuel costs, it was found that this reduction increases with the number of platooning trucks. Alike, the total fuel costs decrease with an increasing number of platooning trucks. The total reduction in fuel costs can be as high as 6,9% for all trucks together, at the highest numbers of platooning trucks.

On the other hand, it was investigated whether the distance of the routes that the trucks must cover affects the size of the benefits of truck platooning. It was found in this research that this is not the case. Multiplying the total length of the routes, i.e. multiplying both the parts that can be driven in a platoon and that must be driven independently with the same factor, does not affect the relative reductions of truck platooning. Allowing 40 platooning trucks to be used, the benefits remain stable at values close to 6,9% for the entire fleet of trucks. However, when the distances that must be driven independently are held constant, while multiplying the distances that can be driven in a platoon with different factors, it is found that the benefits of truck platooning increase with the multiplication factor. This can be explained by a varying ratio of kilometres driven in a platoon and driven independently. For higher values of this ratio, higher reductions in fuel consumption can be obtained. To achieve a higher level of this ratio, one could fall back on the network effects of truck platooning. If the number of trucks on the road with platooning technology installed is higher, the ratio between the kilometres can consequently simply be increased, at is it is easier to create a platoon.

For both points mentioned above, it can be concluded that more trucks with platooning technology increases the benefits of truck platooning for the society as a whole. The question is then who is willing to take the risk and invest in the technology as first, without knowing whether enough will be saved on fuel costs to earn the investment costs back. There are possibly tons of potential first users of the technology that one can think of, but as the focus in the case study was on a supermarket, it was an easy step to investigate whether supermarkets are suitable first adopters. It was found that the savings on fuel costs are sufficient to cover the annual investment costs of €511 per truck. This means that supermarkets are able to bear the investment costs while knowing for sure that it will earn the invested money back. That the trucks of supermarkets cover only relatively short distances between the distribution centre and the stores does not matter for the benefits that platooning provides, as was elaborated before. The fact that a supermarket operates multiple trucks, heading toward stores that are located relatively close to each other, makes that supermarkets are viable first adopters. In this way, they can ensure that the ratio between kilometres driven in platoon and driven independently is sufficiently high to result in enough fuel consumption reductions. There is however a limit to the number of trucks that should be equipped with the platooning technology. For some stores, located close to the DC or far from each other, too little is saved on fuel costs such that the investment costs are not justified. In these cases, it is better to let the trucks drive independently. But overall, the supermarket used in this case study could positively benefit from employing truck platooning.

The analysis performed in this research has some limitations that could be pointed at. Several values that were used as parameters in the model are rough estimates, since the real values could not be obtained. Examples are the fuel consumption of the trucks, the number of loads that each store wished to receive and at what time the loads should arrive. Also, the model assumes that every metre that the routes between the DC and the stores have in correspondence can be driven in a platoon, and leads to a fixed reduction in fuel consumption of 10%. It ignores here the possibilities of congestion, traffic lights and other factors that must be dealt with, which could limit the platooning opportunities or the resulting reduction in fuel consumption. The 10% reduction in fuel consumption itself is also a rough estimate based on the current existing literature, where the realistically obtainable reduction is not known yet. Due to the relative short distances, it could be possible that the potential reduction in fuel consumption is not fully achieved, as the reduction is probably only possible at high speeds. This is also ignored in the model. Furthermore, the model only considerers the move from the DC towards the stores. However, the return journey also entails possibilities for truck platooning that are not accounted for here. Finally, the model is only able to create platoons with other trucks of the same supermarket, ignoring the fact that a platoon can also be made with other trucks, increasing the number of kilometres that are driven in a platoon even further.

Recommended for future research is therefore to investigate the effects of factors that leads to braking and pulling up again, such as traffic lights and congestion, on the potential reduction in fuel consumption that platooning can provide. This may result in different, probably lower reductions. On the other hand, it could be investigated what the effects are of creating platoons with more than two trucks, which may increase the reduction in fuel consumption. It was found that the length of the routes is irrelevant for the size of the benefits of truck platooning, whereas the ratio between platooned and independently driven kilometres determines how much benefits truck platooning provides. This feeds the urge to investigate whether the platooning service provider mentioned in the literature review is desired, how much this service would additionally add to the fuel consumption reductions and how much trucking firms would be willing to pay for this service. The presence of this service may also pull trucking firms towards investing in the technology, resulting in more potential first adopters.

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Appendix – A1

ID	Store Name	Address	Postal Code	City
0	**Distribution Centre**	**Eikenlaan 265**	**2404 BP**	**Alphen a/d Rijn**
1	's-Gravenzande	Van Geeststraat 31	2692 AC	's-Gravenzande
2	Monster	Molenstraat 46	2681 BS	Monster
3	Den Haag - Forellendaal	Forellendaal 318	2553 LM	Den Haag
4	Den Haag - Leyweg	Leyweg 709/r	2545 GM	Den Haag
5	Den Haag - Theresiastraat	Theresiastraat 145	2593 AG	Den Haag
6	Den Haag - Het Kleine Loo	Het Kleine Loo 270	2592 CK	Den Haag
7	Ypenburg	Oude Kustlijn 82	2496 SE	Den Haag
8	Scheveningen	Tesselseplein 37	2583 HR	Scheveningen
9	Rijswijk - In de Boogaard	Prins Johan Friso Promenade 5	2284 DD	Rijswijk
10	Rijswijk - Dr. Colijnlaan	dr H. Colijnlaan 300	2283 ZA	Rijswijk
11	Rijswijk - H. Ravesteijnplein	H. Ravesteijnplein 40	2282 GT	Rijswijk
12	Voorburg - Herenstraat	Herenstraat 52	2271 CJ	Voorburg
13	Voorburg - Mgr Van Steelaan	Mgr. Van Steelaan 456	2273 GC	Voorburg
14	Voorburg - Essesteijn	Klaverweide 84-90	2272 BV	Voorburg
15	Leidschendam - Damstraat	Damstraat 8	2265 AG	Leidschendam
16	Berkel en Rodenrijs	Molenwerfstraat 25	2651 CK	Berkel en Rodenrijs
17	Zoetermeer - Van Stolberglaan	Van Stolberglaan 23	2713 ES	Zoetermeer
18	Zoetermeer - Dorpsstraat	Dorpsstraat 88	2712 AM	Zoetermeer
19	Zoetermeer - Cadenza	Oostwaarts 109	2711 BB	Zoetermeer
20	Zoetermeer - Oosterheem	Oosterheemplein 480	2721 NJ	Zoetermeer
21	Alphen a/d Rijn - Kerk & Zanen	Provinciepassage 108	2408 EV	Alphen a/d Rijn
22	Alphen a/d Rijn - Julianastraat	Julianastraat 45	2405 CG	Alphen a/d Rijn
23	Alphen a/d Rijn - Baronie	Baronie 88	2404 XH	Alphen a/d Rijn
24	Alphen a/d Rijn - Ridderhof	Ridderhof 47	2402 EN	Alphen a/d Rijn
25	Hazerswoude	Rijndijk 248	2394 AN	Hazerswoude
26	Voorschoten	Veurseweg 18	2252 AA	Voorschoten
27	Leiden - Kennedylaan	Kennedylaan 118	2324 EZ	Leiden
28	Leiden - Levendaal	Levendaal 20	2311 JL	Leiden
29	Leiden - Kooiplein	Philipsburgstraat 15	2315 ZB	Leiden
30	Leiderdorp	Poortwacht 139	2353 ED	Leiderdorp
31	Valkenburg Z.H.	Hoofdstraat 104-106	2235 CK	Valkenburg
32	Rijnsburg	Oegstgeesterweg 48	2231 AZ	Rijnsburg
33	Katwijk	Voorstraat 49	2225 EL	Katwijk
34	Sassenheim	Koetsierweg 7	2171 NL	Sassenheim
35	Lisse	Grachtweg 47	2161 HL	Lisse
36	Nieuw-Vennep	Kalslagerring 25	2151 TA	Nieuw-Vennep
37	Rotterdam - Beverwaard	Rhijnouwensingel 227-237	3077 VD	Rotterdam
38	Hoogvliet - Oude wal	Oude Wal 37	3193 EM	Hoogvliet
39	Vlaardingen	Parallelweg 8	3131 DG	Vlaardingen
40	Maassluis	Koningshoek 93101	3144 BA	Maassluis

Table A1: List with addresses of the distribution centre and the 40 stores that are included in the case study

Appendix – A2

Time span:			Daily	Daily	Annual	Annual	Annual	Annual	Annual		Annual
Number of trucks	**Distance in platoon (km)**	**Distance in platoon (%)**	**Fuel consumption**	**Fuel costs**	**Fuel costs**	**Fuel cost reduction (€)**	**Fuel cost reduction (%)**	**Marginal reduction in fuel costs**	**Fuel cost reduction/ platoonin truck**	**Total #trucks required**	**Fuel costs/truck**
0	0	0.0%	1104	1402	420635	0	0.0%			36	11684.32
2	448.8	12.2%	1090.6	1385.0	415506	5130	1.2%	1.2%	2564.89	37	11229.88
4	902.4	24.5%	1077.0	1367.7	410321	10314	2.5%	1.2%	2578.61	37	11089.76
6	1197.6	32.5%	1068.1	1356.5	406947	13689	3.3%	0.8%	2281.43	38	10709.13
8	1277	34.7%	1065.7	1353.5	406039	14596	3.5%	0.2%	1824.51	37	10974.04
10	1674.8	45.5%	1053.8	1338.3	401492	19143	4.6%	1.1%	1914.30	36	11152.57
12	1860.6	50.6%	1048.2	1331.2	399369	21267	5.1%	0.5%	1772.22	36	11093.58
14	2005.4	54.5%	1043.9	1325.7	397714	22922	5.4%	0.4%	1637.27	36	11047.6
16	2135.4	58.0%	1040.0	1320.8	396228	24408	5.8%	0.4%	1525.48	36	10669.75
18	2262	61.5%	1036.2	1315.9	394781	25855	6.1%	0.4%	1436.37	3	11043.09
20	2287.2	62.2%	1035.4	1315.0	394493	26143	6.2%	0.8%	1307.13	37	10661.97
22	2363.2	64.2%	1033.1	1312.1	393624	27011	6.4%	0.2%	1227.79	36	10934
24	2369.4	64.4%	1032.9	1311.8	393553	27082	6.4%	0.0%	1128.43	36	10932.03
26	2380.2	64.7%	1032.6	1311.4	393430	27206	6.5%	0.5%	1046.37	36	10928.6
28	2461.8	66.9%	1030.2	1308.3	392497	28138	6.7%	0.2%	1004.94	36	10902.7
30	2499	67.9%	1029.1	1306.9	392072	28564	6.8%	0.1%	952.12	37	10596.54
32	2492.8	67.7%	1029.2	1307.1	392143	28493	6.8%	0.0%	890.40	38	10319.55
34	2549.8	69.3%	1027.5	1305.0	391491	29144	6.9%	0.2%	857.18	36	10874.76
36	2551.1	69.3%	1027.5	1304.9	391475	29160	6.9%	0.0%	810.01	38	10301.98
38	2551.2	69.3%	1027.5	1304.9	391475	29160	6.9%	0.9%	767.37	38	10301.98

Table A2: Results of the case study, first hypothesis (section 4.1) with an increase of platooning trucks in steps of 2

Appendix – A3

Time span:				Daily	Daily	Annual	Annual	Annual	Annual
Distance multiplication factor	**Total distance**	**Distance in platoon (km)**	**Distance in platoon (%)**	**Fuel consumption**	**Fuel costs (€)**	**Fuel costs (€)**	**Saving (€)**	**Saving (%)**	**Fuel costs per distance unit**
1	3680	2515	68.4%	1028.6	1306.3	391884	28751	6.84%	391884.4
2	7360	5031	68.4%	2057.1	2612.5	783764	57507	6.84%	391882.1
3	11040	7475	67.7%	3087.8	3921.5	1176462	85444	6.77%	392154.2
5	18401	12555	68.2%	5143.5	6532.2	1959674	143504	6.82%	391934.7
10	36801	25128	68.3%	10286.5	13063.8	3919141	287213	6.83%	391914.1
15	55202	38130	69.1%	15416.6	19579.0	5873706	435826	6.91%	391580.4

Table A3: Results of the case study, second hypothesis (section 4.2) about different distances

Appendix – A4

Time span:				Daily	Daily	Annual	Annual	Annual	Annual
Distance multiplication factor	**Total distance**	**Distance in platoon (km)**	**Distance in platoon (%)**	**Fuel consumption**	**Fuel costs (€)**	**Fuel costs (€)**	**Saving (€)**	**Saving (%)**	**Fuel costs per distance unit**
1	6195.5	2515.4	40.6%	1783.2	2264.6	679395	28751	4.06%	679394.6
2	8710.9	5030.8	57.8%	2462.3	3127.2	938154	57502	5.78%	469076.9
3	11226.3	7546.2	67.2%	3141.5	3989.7	1196913	86253	6.72%	398971
5	16257.1	12577	77.4%	4499.8	5714.8	1714431	143755	7.74%	342886.3
10	28834.1	25154	87.2%	7895.6	10027.4	3008227	287510	8.72%	300822.7
15	41411.1	37731	91.1%	11291.4	14340.1	4302023	431265	9.11%	286801.6
20	53988.1	50308	93.2%	14687.2	18652.7	5595819	575020	9.32%	279791
25	66565.1	62885	94.5%	18083.0	22965.4	6889615	718776	9.45%	275584.6

Table A4: Results of the case study, second hypothesis (section 4.2) about different distances

Appendix – A5

Number of trucks	Annual Fuel cost reduction (€)	Annual Investment costs	Annual Net saving (€)	Annual Net saving (%)
0	0	0	0	0.0%
2	5130	1022	4108	1.0%
4	10314	2044	8270	2.0%
6	13689	3066	10623	2.5%
8	14596	4088	10508	2.5%
10	19143	5110	14033	3.3%
12	21267	6132	15135	3.6%
14	22922	7154	15768	3.7%
16	24408	8176	16232	3.9%
18	25855	9198	16657	4.0%
20	26143	10220	15923	3.8%
22	27011	11242	15769	3.7%
24	27082	12264	14818	3.5%
26	27206	13286	13920	3.3%
28	28138	14308	13830	3.3%
30	28564	15330	13234	3.1%
32	28493	16352	12141	2.9%
34	29144	17374	11770	2.8%
36	29160	18396	10764	2.6%
38	29160	19418	9742	2.3%

Table A5: Results of the case study (section 4.3) about net savings