Truck Platooning

Enablers, Barriers, Potential and Impacts

Transport, Infrastructure and Logistics
Master thesis

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by

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Preface

This thesis is submitted in partially fulfillment of the requirements for the degree of MSc. in Transport, Infrastructure and Logistics at Delft University of Technology. The research was carried out in cooperation with Connekt/ITS Netherlands. This research presents the enablers, barriers, potential and impacts of truck platooning. The report is aimed at the transport market, policymakers and scientists in the field of transport innovation.

I would like to thank my graduation committee for their guidance and support during this research. Their experience and knowledge in the field of transport and logistics kept me on the right track. Bart van Arem helped me finding this fascinating thesis topic and provided me with useful feedback. Marije de Vreeze was always available for small and big questions. She made sure that multiple perspectives were highlighted and introduced me to several experts in the ITS sector. I had inspiring talks with Bart Wiegmans. He taught me the importance of report structures and encouraged me to write an article about truck platooning. Ron van Duin shared his enthusiasm about truck platooning and logistics and gave me constructive feedback.

Furthermore, my gratitude goes to Connekt for the inspiring and changing working environment. My colleagues at Connekt provided me valuable input for my thesis but they also gave enjoyable moments and time to relax. Especially the weekly meetings with my Connekt/ITS colleagues, Marije, Nick, Tom, Marina and Sri, were inspiring and helpful.

Finally, I would like to mention that this thesis will not be my last contribution to science.

Bon Albin Bakermans
Delft, August 2016

Summary

Executive summary

Truck platooning refers to the automated operation of multiple trucks. High expectations rest on truck platooning as to alleviate negative impacts caused by road freight transport like congestion, accidents and pollution. Furthermore, driver shortages may be partially solved by the concept of truck platooning. This study identified enablers and barriers of truck platooning and assessed their effect on the potential implementation of the concept. The implementation and possible adoption of truck platooning as a transport mode is a complex and uncertain process. The magnitude of the consequences of platooning are in general unknown and many different stakeholders should be involved in the implementation process. Based on this research it can be concluded that several barriers still have to be mitigated and that cooperation between different competing companies and industries is essential for the successful implementation of truck platooning.

Extended summary

The implementation of automated systems in both freight and passenger vehicles develops gradually towards fully automated vehicles driving on public roads. Early implementation phases of vehicle automation such as adaptive cruise control and lane keeping assistance are already increasingly being implemented. A promising next phase in automation is truck platooning. This technique enables trucks to drive close behind each other by using cooperative adaptive cruise control. In this way, the first truck (leader) will take the lead and determines the speed while the following trucks are communicating with the leader truck and are therefore able to respond automatically and immediately to breaking and accelerating. Road tests showed that a platoon of trucks may be technically able to participate in real life traffic. However, several barriers need to be mitigated before platooning trucks will actually drive on public roads. Next to that, the magnitude of the benefits of truck platooning for shippers and carriers is still uncertain.

Identification of enablers and barriers

If one compares truck platooning with other freight transport innovations, truck platooning is unique in the sense that it both involves automation and uses existing public infrastructure. A theoretical framework with product characteristics, user requirements and external factors is able to evaluate freight transport innovations and identify enablers and barriers for implementation and adoption. Based on a literature review, five different freight transport innovations are evaluated (i.e. automated guided vehicles, longer heavier freight vehicles, underground logistics system, CombiRoad and Districtvaart). Those five innovations are related to truck platooning as they show similarities in automation or in usage of existing public infrastructure. Based on these five innovations, trialability and compatibility are found to be critical indicators for the implementation of truck platooning. Trialability can be created with several pilot projects and real life cases. Next to that, collaboration between different competing stakeholders is crucial for the implementation of platooning. The three most important examples of cooperation are given below:

- truck manufacturers should cooperate to enable multibrand truck platooning,
- carrier cooperation is needed to establish the actual platoons on the road,
- cooperation between national road authorities is needed to allow for cross-border truck platoons.

Enablers and barriers for the implementation and adoption of truck platooning

When a certain aspect is perceived as positive for the implementation and adoption of truck platooning it is categorized as an enabler, whereas the opposite applies for barriers. Based on a literature study and the comparison of truck platooning with the five above mentioned transport innovations, enablers and barriers for truck platooning are found. The most important enablers and barriers are given in the table below.

Enablers	Barriers
Use of existing and public infrastructure	Bundling of goods is needed
Realization of fuel savings	Platoon formation time
Larger truck driver productivity	Potential reverse modal shift
Increase in road safety	Many different stakeholders with conflicting interests
Increase in infrastructure capacity	Cooperation between shippers is needed
	Uncertain consequences make adopters hesitant
	Low penetration rate at first stages of implementation

Table 1: Found enablers and barriers for the implementation and adoption of truck platooning.

Potential freight flows for truck platooning

Several enablers and barriers of truck platooning are assessed with road freight transport data and a transport model using several future platooning scenarios. The road data comprises trips that are made with Dutch freight vehicles. This means that both national and international flows are considered. Though, in reality the number of international trips will be higher because also freight vehicles from other nationalities travel from and into the Netherlands. The first scenario considers fuel consumption savings as the only benefit of truck platooning, which may be realistic in the first implementation stages of platooning. The analysis showed that only little freight flows are feasible for truck platooning in this scenario. Especially when the penetration rate drops, the adoption of truck platooning is not beneficial. For example, less than 4% of all freight trips is feasible for platooning with a penetration rate of 50%. Whereas, 18% of the trips is feasible for a penetration rate of 100%. Moreover, it is found that the volume of the freight flows is more important than the trip distances of the flows. In other words, most feasible flows have a high number of trucks per hour but the origin and destination are not necessarily located far apart. This also means that cross-border transport with platoons is not essential for successful implementation of the concept. The analysis of the first scenario is based on dynamic platoon formation, cross-border transport may be important for coordinated platoon formation. In the way, platoons of trucks are formed with agreements and planning beforehand. The second platooning scenario is based on driver productivity optimization and assumes that platoons of trucks are able to cover longer distances than regular trucks. Coordinated platoon formation is important because the truck flows for these longer distances (±800 km) become small. Note that legislation does not yet provide rules or guidelines for longer trip distances because the consequences for following drivers are still unknown. The third scenario assumes a labor cost reduction for truck platooning. Such a reduction may be possible when drivers in following trucks are not needed anymore. Moreover, the relative labor cost may decrease when drivers in following trucks are able to perform other activities. It is found that a decrease in labor costs may significantly contribute to the feasibility of truck platooning. Platooning in this scenario is beneficial for more than half of all Dutch truck trips when a penetration rate of 50% is used. Though, when the penetration rate decreases, the number of feasible trips also decreases rapidly. Therefore, it can be concluded that cooperation to establish multibrand platooning is indeed important, i.e. high penetration rates can only be achieved with multibrand platooning.

Estimation of modal shift with freight transport model

A potential modal shift due to the adoption of truck platooning is assessed with the Dutch freight transport model BasGoed. The model estimates freight flows of rail, road and inland waterway transport between origin and destination zones. The presence of truck platooning is modelled by changing the properties of regular road transport. A modal shift from rail and inland waterway transport to road transport can be noticed due to the implementation truck platooning. The scenarios as described above show

significant modal changes. Especially a decrease in labor cost will result in a shift. When only fuel savings are taken into account, reverse modal shifts up to 5% can be found due to the implementation of truck platooning. An increase in road freight transport up to 18% can be noticed when also labor costs savings are included. This also results in a decrease of around 15% for the other inland modes. It is also found that international or cross-border flows are more sensitive for a shift towards road transport. Therefore, it can be concluded that restrictions on cross-border road transport with platoons may be an effective policy measure to avoid a reverse modal shift. On the other hand, such restrictions will also decelerate the adoption of truck platooning. Finally, the transport model shows that the adoption of truck platooning causes an increase in total transported freight volume.

Outlook and perspectives of governments and transport companies

This research focuses on the perspectives of governments and transport companies. Investments of governments in the concept of truck platooning can be partially justified as the concept may result in several societal benefits. Moreover, platooning becomes more beneficial when the penetration rate is high, and in the first implementation stages subsidies may be needed to reach a certain critical mass. Though, truck platooning may also result in negative consequences, such as a reverse modal shift and a higher road usage. For governments, it is advised to seriously consider their involvement in the implementation of truck platooning. An innovation becomes more durable when the actual transport market is willing to adopt the technology. It is advised to contribute to the research into platooning consequences as a better understanding of the impacts may lead to a clear policy towards truck platooning. Carriers and shippers represent the market pull of truck platooning and are currently relatively latent towards platooning. This can be explained by the fact that platooning trucks are not yet available and the fact that legislation does not yet provide in rules for platooning. However, it is advised to start discussions concerning truck platooning because early involvement may lead to more beneficial platooning circumstances.

Conclusion

The implementation and possible adoption of truck platooning as a transport mode is a complex and uncertain process. This research study tried to elucidate this complexity by indicating the enablers and barriers for the implementation of truck platooning and by estimating the effect of those enablers and barriers. With the used transport data and model, for some enablers and barriers it was possible the estimate to effect on the implementation of truck platooning. Those enablers and barriers are summed up below:

- Realization of fuel savings;
  From the transport data base analysis one can conclude that truck platooning with only fuel consumption savings as benefit is probably not feasible. Moreover, the order of fuel savings in practice is still uncertain and also depends on the interaction of a platoon with other road users. Fuel savings will contribute to the implementation of truck platooning, but might not be as important as other enablers.
- Larger truck driver productivity;
  Automation of trucks and its related increased driver productivity are perceived as a enabler because it may result in longer trips distances or lower relative labor cost. Both consequences largely contribute to the profitability of truck platooning. However, it is expected that it will take at least one decade before the needed automation levels are available in practice.
- No cross-border transport with platoons;
  Transport data analysis revealed that most feasible platooning trips have their origin and destination relatively close to each other (less than 100km). Therefore, it can be concluded that this barrier is relatively small. Note that several assumptions were made to come to this conclusion, i.e. neglecting network assignment.
- Low penetration rate at first implementation;
  A low number of trucks that are able to platoon during the first implementation stages are perceived as an important barrier. The transport data and model also show that lower penetration rates are disadvantageous for truck platooning.

Note that this are only the enablers and barriers that are assessed with the transport data and model. The earlier mentioned enablers and barriers will also have a large effect on the actual implementation of truck platooning. Pilot projects and real-life cases should show the effect of the other enablers and barriers, such as the potential increase in road safety.

Contents

Nomenclature

Acronyms

ACC	Adaptive cruise control
AGV	Automated guided vehicle
CACC	Cooperative adaptive cruise control
CBS	Statistics Netherlands
COROP	Coordination Commission Regional Research Programme
DATP	Driver assistance truck platooning
ECT	Europe container terminals
ITS	Intelligent transportation systems
IWW	Inland waterway
LKA	Lane keeping assist
LHV	Longer heavier freight vehicle (LZV in Dutch), also Ecocombi
NDW	Dutch national datawarehouse for traffic information
NRA	National road authority
NSTR-1	Standard goods classification for transport statistics
OD	Origin-destination
OEM	Original equipment manufacturer
SAE	Society of automotive engineers
RDW	National road traffic department
TEU	Twenty-foot equivalent unit
ULS	Underground logistics system
V2I	Vehicle to infrastructure communication
V2V	Vehicle to vehicle communication
V2X	Vehicle to everything communication
VoT	Value of time

Terminology

Autonomous vehicles	Automation of driving with unconnected systems. A vehicle takes care of its own environment without V2I or V2V.
Automated vehicles	Refers to both autonomous and cooperative driving vehicles or a combination of both. Also, the automation of vehicles is used in this sense.
Cooperative vehicles	Automation of driving with communication and connected systems. Communication is possible with other vehicles or with infrastructure.
Coordinated formation	Platoons of trucks are formed with agreements and planning.
Dynamic formation	Truck platooning in which a platoon is formed without any coordination. Also referred to as spontaneous formation, on-the-fly and ad hoc platooning.
Freight flow	A specified amount of goods transported between an origin and a destination zone.
Modal split	Distribution of freight trips over the three inland modalities, i.e. road, rail and inland waterway. Based on the amount of tonnes transported.

Multibrand platooning	The possibility to platoon with trucks of another brand. In general platooning system is needed for multibrand truck platooning.
Penetration rate	Percentage of trucks that is able to platoon.
Reverse modal shift	A shift from rail and inland waterway transport towards road transport.
Trip distance	The distance covered between the centroids of an origin zone and a destination zone. The actual distance is estimated by multiplying the Euclidean distance with a route factor.
Truck flow	Number of trucks driving on a highway per hour. The production of trucks is assumed to be uniformly distributed.
Value of time	Factor to translate a certain time loss into a monetary value.

1 Introduction

Automation of vehicles is developing rapidly and currently, we are in an era that the computer may take over our tasks and responsibilities in traffic. Different projects have demonstrated that self-driving vehicles are able to participate in real life traffic. Noticeable is the Google Self-Driving Car Project which showed that an autonomous car may be able to safely travel on public roads (Google Self-Driving Car Project, 2016). Also pilot projects that use automated vehicles as public transport service are performed. An example is the WEpods project that tries to find the potential for automated road public transport (Correia, 2016). A six person self-driving vehicle that is allowed to drive on public roads was created. Vehicle automation is also developing in the freight transport sector. This research focuses on the implementation of automation in the freight transport sector. Different implementations of transport automation are depicted in Figure 1.1.

(a) Google Self-Driving Car (b) WEpod (c) Truck platoon

Figure 1.1: Examples of automation in private, public and freight transport.
Sources: Google Self-Driving Car Project, 2016; WEpods, 2016; Scania Group, 2016.

A promising innovation in the freight transport sector is truck platooning. This innovation may (partly) solve different problems for road freight transport. One can think of environmental issues and emissions, or the expected shortage of truck drivers and congestion or the availability of road infrastructure.

1.1. Problem statement

Economic growth is strongly related to a growth of the freight transport demand and an increase in freight kilometers travelled (Hummels, 2007). A global trend of increasing freight traffic can be noticed and it is expected that this trend will continue in the following decades (Rodrigue et al., 2013). Road freight transport has major competitive advantages, such as an extensive infrastructure network and the relative high speed of the mode. It is therefore that road transport takes the largest share among inland freight transport, e.g. 75% of the total freight in Europe in 2012 was transported by road (Eurostat, 2014). Innovations in this sector may result in major implications for whole transport supply chains.

Throughout history a lot of developments and innovations in the road transport sector can be noticed (McKinnon, 2009). Automation and intelligent transport systems (ITS) on public roads are a new chapter in this history. One first important innovation of automation on public roads is truck platooning. Truck platooning is the driving of trucks close behind each other with the assistance of automated driving technologies. Platoons of trucks may result in less fuel consumption and improvements in productivity. Fuel costs and driver wages are the two most significant operating costs for trucks (Ford Torrey and Murry, 2015; Levinson et al., 2005). Since truck platooning may decrease these costs, the concept may become interesting in the near future. Moreover, truck platooning may result in less congestion on highways and a reduction in emissions. Large scale implementation may therefore result in more sustainable road freight transport.

As truck platooning is a new concept in road transportation, currently the main focus is on the technology. Some successful tests with automated trucks driving in a platoon have already been carried out (Larson et al., 2015; Robinson et al., 2010). The automotive industry, governments and road authorities already invested a lot to accomplish these first platoons on public roads. As the first platoons of trucks drove on public highways, the transport sector is now needed to further develop the concept of truck platooning.

The first steps in implementing truck platooning will probably be the hardest (Janssen et al., 2015). This is because the value of a truck equipped with platooning technology is dependent on the number of other trucks that are equipped with platooning technology. When more trucks are able to cooperate with each other the relative benefits will be higher. So, early adopters should be convinced about the benefits of implementing truck platooning. Currently, freight transport results in an extensive road usage and evidently this leads to negative side effects. Truck platooning might partly solve some of these effects, such as congestion, emissions and road accidents. While the truck platooning concept is currently mainly based on a technology push, it should shift to a market pull for further development and implementation. Therefore, the market or the transport and logistics sector needs to know when truck platooning is competitive and how it should be implemented.

1.2. Objective and research questions

The objective of this research is to find out whether the concept of truck platooning is a viable transport alternative for the transport and logistics sector. To determine whether the transport market should implement truck platooning, the characteristics of truck platooning and the needs of the transport market will be analyzed. Next to that, the potential impacts of truck platooning need to be identified.

The objective can be translated in the following main research question:

Which enablers and barriers will the concept of truck platooning face and how do these affect the potential implementation of the concept?

To answer the main question, some additional research questions are defined:

1. What are the characteristics of truck platooning as a transport mode?
2. Which needs in the transport sector can be fulfilled by the implementation of truck platooning?
3. What determines whether innovations in freight transport are successful?
4. Which market conditions are favorable for the implementation of truck platooning?
5. How can the expected impact of truck platooning on other transport modes be modelled?

1.3. Research methodology and framework

The basic structure of this research is depicted in Figure 1.2. Different scientific methods are used in the different chapters. The characteristics of autonomous and cooperative driving are described and related to truck platooning in Chapter 2. A literature study is conducted to find the potential and expected impacts of truck platooning. To create a clearer image of the current status of the truck platooning concept, the most important stakeholders are described and positioned in a push and pull framework.

The concept of truck platooning as freight transport innovation is positioned in a broader perspective in Chapter 3. A theoretical innovation framework is created to find barriers and enablers of five freight transport innovations. The five innovations have on some aspects similarities with truck platooning. The barriers and enablers are analyzed based on literature and then related to the concept of truck platooning. The importance of the found barriers and enablers for the implementation of truck platooning is estimated with a literature study. Critical developments for the adoption of truck platooning are then found with the help of experts.

Potential freight flows for truck platooning and its corresponding impacts are estimated through a transport model. Chapter 4 shows the quantitative perspective of truck platooning. Freight transport data of the Netherlands is used to evaluate the potential of the concept. Truck platooning scenarios and requirements are created with the analyses of previous chapters. The requirements are used to identify beneficial freight flows for truck platooning. Different scenarios result in different beneficial freight flows. A potential modal shift is modelled with the transport model by adjusting the characteristics of road transport.

Chapter	Method and approach	Result
1. Introduction		Research aim Scientific relevance
2. Truck platooning Research question 1 and 2	Literature study	Characteristics and impact Market and playing field
3. Transport innovation Research question 3 and 4	Literature study	Innovation framework Related innovations Barriers and enablers
4. Potential and impacts Research question 5	Data analysis Transport model	Favorable flows and conditions Impact of platooning
5. Integration	Combining research methods	Thesis relevance Platooning perspectives
6. Conclusion Main research question		Conclusion Recommendations Reflection

Figure 1.2: Research structure and thesis outline.

The theoretical framework used in this thesis is presented in Figure 1.3. The framework shows the technology push and market pull of the truck platooning implementation problem. Both sides are analyzed and used in combination with external factors to find the barriers and enablers. Based on freight flow data and the product characteristics an evaluation is done with a transport model to quantify the potential of the concept. Finally, the conducted analyses are used to review the shippers' perspective on truck platooning and determine its potential implementation.

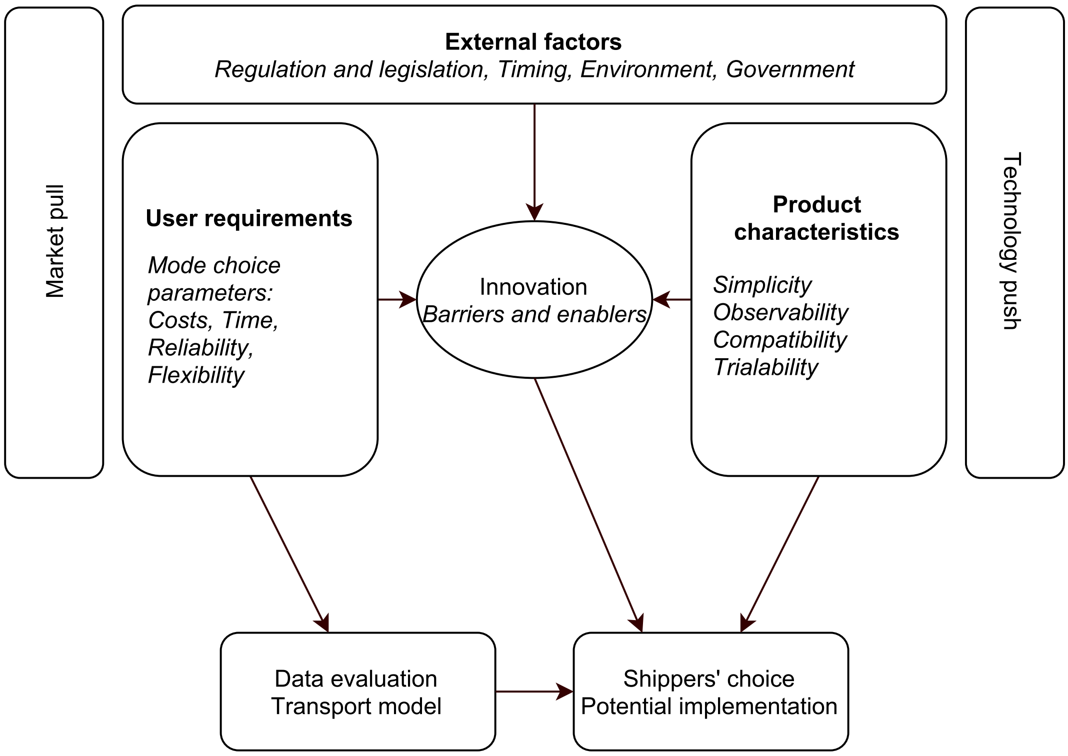


Figure 1.3: Overall theoretical framework used in this thesis research.
Source: Based on Visser et al. (2008); Van der Straten et al. (2007); Rogers (2003); Tidd et al. (2001).

1.4. Scientific relevance

Existing literature about truck platooning mainly focuses on the technological feasibility of truck platooning (e.g. Alam et al., 2015 and Larson et al., 2015) or potential formation strategies for platoons (e.g. Liang et al., 2013 and Caltagirone et al., 2015). On the contrary, this thesis focuses on the actual market of the truck platooning concept and evaluates its potential from a market perspective. The results of this research may serve as guidance for policymakers, who have the opportunity to enforce or mitigate the enablers and barriers of the truck platooning concept. The transport market may also benefit from this research, as truck platooning and its potential are analyzed in detail. Carriers and shippers are becoming more interested in the technology of truck platooning and this research shows which freight flows are beneficial for truck platooning under different circumstances.

2

Technical and market characteristics of truck platooning

Truck platooning is generally explained as the automated and cooperatively driving of trucks close behind each other (Alam et al., 2015). This chapter describes the characteristics of truck platooning. First, the idea of autonomous and cooperative driving trucks is explained. After that, the expected and assessed consequences of truck platooning are discussed in Section 2.2. The playing field and truck platooning market are described and analyzed in Section 2.3. Finally, the answer to research question 1 and 2 is given in the conclusion of this chapter.

2.1. Technical characteristics and implementation

Developments in self driving vehicles are based on two concepts: autonomous driving and cooperative driving (Wilmink et al., 2014). Both concepts bring their own advantages and difficulties. Autonomous driving may result in less labour costs and more safety (Janssen et al., 2015). Cooperative driving may result in less fuel consumption, more efficient road usage and also more safety (Janssen et al., 2015; Van Arem et al., 2006). Below, both concepts are elaborated for truck platooning.

2.1.1. Autonomous driving trucks

Autonomous vehicles are automated vehicles that do not communicate with other vehicles and only monitor the outside world. This section uses the term autonomous driving vehicles to distinguish from cooperative driving. Reference is made to both concepts if the term automated driving is used. Autonomous driving in the freight transport sector has already been successfully deployed in non-public areas. Examples are the automated guided vehicles (AGV) at several port terminals (Fumarola and Versteegt, 2011) and the use of automated storage systems in warehouses or distribution centers. Truck platooning may be the first step in the automation of freight transport on public roads. Systems that assist the driver are already commercially available, examples are adaptive cruise control (ACC) and lane keeping assist (LKA) (Hoogendoorn et al., 2013).

Vehicle automation levels

The degree or level of automation may vary amongst different truck platoons. Several sources described vehicle automation in different levels (e.g. Smith (2013); Gasser and Westhoff (2012)). Generally, these levels vary between no automation or driver only and fully automation. Truck platooning may be deployed in different levels of automation. The Society of Automotive Engineers (SAE) developed a framework to categorize different levels of automation. These levels of automation can be distinguished in two categories; automation in which the human driver monitors the driving environment and automation in which the system monitor the driving environment, see Figure 2.1. The earliest or simplest stages of truck platooning belong to the first category. In this stage the platooning system only determines the following distance of the truck. Therefore longitudinal control is automated and the truck driver manages lateral control. An example of this technique is the platoon project conducted by Peloton Technology (Roeth, 2013). Main goal of this project is a decrease in the fuel consumption of trucks on highways. All skills of the drivers are still needed, however the system provides a fast breaking mechanism and therefore the longitudinal spacing between trucks can be decreased. The system uses vehicle to vehicle communication. Such a system can be categorized as SAE level 2. Truck platooning in SAE level 2 is also generally referred to as driver assistance truck platooning (DATP). ACC can be categorized as SAE level 1 and is already widely available in the trucking industry.

A next stage in truck platooning arises when the truck also monitors the driving environment. For this stage also vehicle to infrastructure communication is needed. Truck platooning can be executed for both SAE level 3 and 4. For level 3 the driver of the vehicle fulfills a fallback option. Initially, the leader truck of a platoon will have an active driving role, whereas the drivers in the following truck(s) have a passive role. For level 4 automation the drivers in the following truck(s) are not needed anymore for primary driving functions. Drivers are however still needed for driving under specific conditions or when the platoon splits. An example of such a level of automation is the German KONVOI project (Wille et al., 2007). The first driver operates manually, whereas the other vehicles follow automatically. In this case the system provides longitudinal and lateral guidance. Drivers in the following trucks are still needed for the monitoring of the system and the driving in specific environments. The PATH platooning research project developed a truck platooning technique in SAE level 4 (Browand et al., 2004). The leader truck in the project was also highly automated and a driver was only needed as fallback option.

Level 5 corresponds to full automation; all driving functionalities are now performed by the system. The vehicle or truck is able to drive without a driver regardless of the driving conditions. Table 2.1 shows the different levels of automation and the tasks that the automated system will fulfill. The table also shows expected implementation dates according to ERTRAC (2015), these will be further explained below.

SAE level		Steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	Reference truck platooning project	Expected earliest implementation (ERTRAC, 2015)
5	Full Automation					2035
4	High Automation	**System is responsible**			KONVOI SARTRE	2020
3	Conditional automation					2020
2	Partial Automation				Peloton Technology Traffic Jam Assistance	2017
1	Driver Assistance	**Human driver is responsible**			Truck equipped with ACC or LKA	Already implemented in practice
0	No Automation				Regular trucks	

Table 2.1: Vehicle automation levels by SAE and the tasks that a system provides.
Sources: SAE International, 2014; ERTRAC, 2015.

2.1.2. Cooperative driving trucks

Short spacing between driving trucks can be achieved with cooperative adaptive cruise control (CACC) (Van Arem et al., 2006). Using this technique, the trucks communicate with each other and are able to form a platoon. The trucks in a platoon use radar and vehicle to vehicle communication to cooperate with each other. Cooperation is needed for closer distances/spacing between vehicles and for safety reasons. Besides that, cooperation or V2V communication may eliminate shock waves and smooths the traffic flow. Four levels of cooperation for truck platooning can be distinguished. First, no cooperation is involved in driver assistance systems, i.e. these systems only monitor the environment. Then, cooperation can be arranged between trucks in advance. For this type of cooperation a platoon needs to be formed before it actually accesses the road. Third, cooperation can be dynamically arranged between trucks. In this case, the truck form a platoon while drive without any arrangements beforehand. Finally, cooperation is possible between all road vehicles.

The relation between automation and cooperation and their corresponding technologies are depicted in Figure 2.1. As described before, it can be expected that both automation and cooperation will develop to higher levels in time. The next section will further elaborate on the potential development in time.

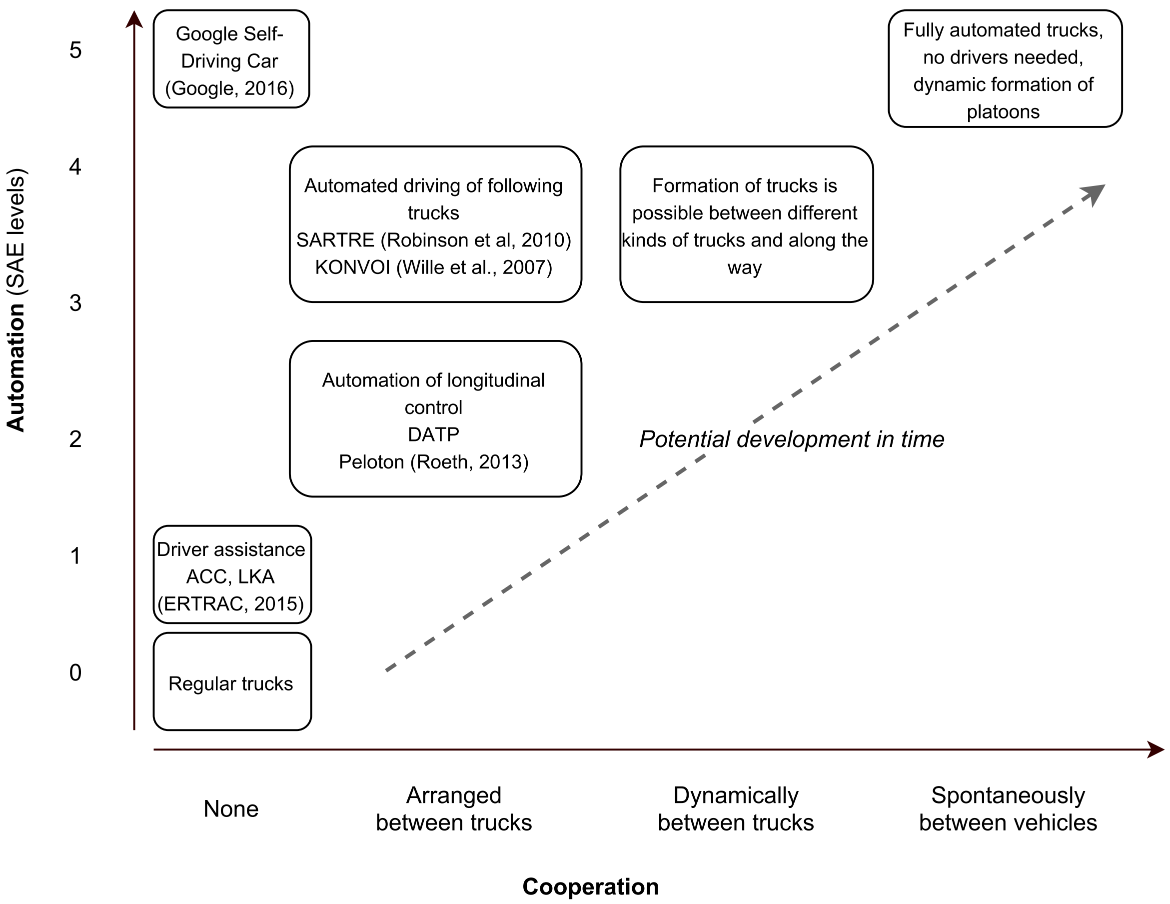


Figure 2.1: Relation between automation and cooperation for trucks.
Source: Based on Puylaert (2016); Janssen et al. (2015); Smith (2013).

2.1.3. Implementation of automation and cooperation for trucks

To give an idea about the current developments concerning truck platooning, different expected implementation paths are analyzed. These give an idea about potential implementation stages of truck platooning and their potential timing. However, these projections only give a rough estimation of the implementation and it is currently still not sure whether the concept of truck platooning will be implemented at all.

An automated vehicle deployment path was developed by ERTRAC (2015), see Table 2.1 for an estimation of the first adoption of different truck platooning stages. Note that the deployment path is mainly based on technological possibilities. ERTRAC (2015) distinguishes between CACC platooning and regular platooning. In this case CACC platooning is only automation in longitudinal direction. Besides that, some actions to diffuse the truck platooning technique were mentioned:

- Show a strong incentive for fuel consumption savings;
- Start with platoons of two trucks in high density truck areas;
- For legal reasons, start with a system where drivers are present in every platooning truck;
- Create a fleet management system for matching trucks between different fleet owners.

During the European truck platooning conference in April 2016 a vision for the implementation of truck platooning was presented (Eckhardt, 2016). This vision shows a potential development path of truck platooning. The vision shows similarities with the expectations of the deployment path of ERTRAC (2015). It also displays a development of both automation and cooperation in time.

Aspect	2016	2020	2025
SAE level	Level 1	Level 3	Level 4
Brand composition	Monobrand	Multibrand	
Length of the platoon	Maximum of 2 or 3 trucks	More than 3 trucks	
Monitoring task	All drivers	All drivers	Only lead driver aware

Table 2.2: Truck platooning implementation path 'Vision 2025', developed by TNO and Rijkswaterstaat.
Source: Adapted from Eckhardt (2016).

Note that the deployment path presented in Table 2.1 and the vision in Table 2.2 are only two of multiple ideas on the implementation dates of automated vehicles. These ideas are presented because they specifically deal with the implementation of automation in freight transport. To position these ideas in a broader perspective reference is made to the work of Shladover (2015). He only expects vehicles with level 5 automation around 2075 on all public highways. Moreover, Shladover (2016) also mentions that operating environment is an important indicator for estimating the implementation date of different automation technologies. For example, the technology of vehicle automation is easier implemented on highways than in urban areas. This means that SAE level 5, in which vehicles are fully automated in every situation or environment are a long way off.

2.1.4. Truck platoon formation

Depending on the penetration of the platooning technique, the type of good, the travel distance and the need of the transport sector, different formation strategies for truck platooning can be sketched (Janssen et al., 2015). One can distinguish two major types of platoon formation; coordinated formation and dynamic formation. These formation types are also related to the level of cooperation. Coordinated formation and dynamic formation need cooperation arranged between trucks and dynamically between trucks respectively.

Coordinated formation

Probably the simplest way of implementing truck platooning is the arrangement of platoons by individual carriers. Carriers may create platoons themselves when the volume of transported goods outweighs one truckload. Carriers create a platoon schedule based on their transport needs. Janssen et al. (2015) described a case for Peter Appel Transport in which was looked at scheduled truck platooning between distribution centers. Peter Appel Transport may benefit from truck platooning because they transport large volumes of freight between distribution centers that are located relatively far apart from each other. Disadvantage for the distribution centers is that they have to handle larger quantity of goods at the same time, which may clog their operations.

In a latter stage platoons of trucks may be formed with a platoon or logistics service provider that manages and plans platoons of trucks. The platoon service provider creates a central point of coordination. The main purpose of this extra service provider is to link different platooning partners and to distribute the benefits of truck platooning. In this way carriers are able to combine their services. However, note that an individual carrier can only benefit from platooning when also other carriers adopt the platooning technique. When individual carriers are not able to combine their trucks, it could be interesting to look at the possibilities for cooperation between carriers. A third party or service provider will coordinate the formation of platoons.

Dynamic formation

Platoons can be formed spontaneous by the automated merging of vehicles, i.e. platoons of trucks can be formed dynamically while driving on the highway. For this case the number of trucks equipped with platooning technology should be high. No platoon schedule is needed for this way of platoon formation. However, probably a central point of coordination is needed to distribute the benefits or the platoon formation. Dynamic platoon formation is also referred to as on-the-fly or ad hoc platooning.

2.2. Consequences of the truck platooning technology

This section discusses the consequences of the implementation of truck platooning. A consequence is the effect of an implementation on the current situation. A distinction can be made between expected and assessed consequences. Expected consequences are based on the knowledge of experts and no quantitative estimation for the consequences is available yet. Assessed consequences are determined results of an implementation by experiments or other studies, such as modelling, simulation or pilots. A comparable framework for consequences of automation was used by Van Arem (2016). Note that all consequences of truck platooning are not yet measured or proved because the technology is not yet implemented in practice. The different consequences are summed up in the Table 2.3 and further discussed in the following analysis. The analysis also discusses whether the consequences result in a positive or negative impact.

Expected consequences	Assessed consequences
Decreased labor costs	Less fuel consumption
Higher asset and equipment utilization	Reduction of emissions
Road capacity optimization	Higher initial investment costs
Higher safety	
Larger road load and degradations	
Engine heating	

Table 2.3: Expected and assessed consequences of the implementation of truck platooning. Source: Based on Janssen et al. (2015); Alam et al. (2015); Robinson et al. (2010).

2.2.1. Expected consequences

These consequences are expected results of truck platooning, however their magnitude and impact is uncertain.

Labor costs

Driver wages or labor costs largely contribute to the total trucking costs (Ford Torrey and Murry, 2015). Especially for higher levels of automation truck driver efficiency can be increased. For example, when drivers in the following trucks of a platoon have fewer tasks or are able to rest during the travel, the drivers are able to perform other tasks. Moreover, driver fatigue is internationally recognized as a significant factor in approximately 15%–20% of commercial road transport crashes (Goel and Vidal, 2013). So, automation may result in financial benefits as drivers work more efficiently. In later stages of truck platooning drivers in following trucks are not needed anymore and even labor costs can be saved.

Asset and equipment utilization

The implementation of truck platooning may result in a reduction of the idle time of trucks and therefore in a better utilization of equipment. This is the case when one of the following trucks, with a rested driver, takes the lead in the platoon. When the driver in the following truck is able to rest during the travel due to the automation of the vehicle, the rested driver may take over the head of the platoon to keep the truck driving. This will result in less overall resting times. An application of this utilization optimization is elaborated in Section 4.2.2 or can be found in the research of Tavasszy (2016).

Road capacity optimization

Several studies were done to estimate the impact of platooning on traffic flows (Milanés et al., 2014; Ploeg et al., 2011; Van Arem et al., 2006). Cooperative adaptive cruise control on passenger cars may contribute to a better traffic flow performance and may therefore increase traffic flow efficiency (Van Arem et al., 2006). Milanés et al. (2014) evaluated CACC on passenger cars in real traffic situations. Road tests showed an overall reduced gap variability while no safety issues were found. It was concluded that the CACC system has the potential to attenuate road disturbances and therefore increase the highway road capacity and the traffic flow stability. However, other sources also mention that ACC with small inter vehicle spaces may also increase disturbances in traffic flows (Ploeg et al., 2011). Velocity variations of leading vehicles may be amplified by following vehicles, resulting in negative side effects.

Other studies focused on the consequence of CACC on trucks. Nieuwenhuijze et al. (2012) and Schermers and Malone (2004) evaluated the traffic flow effects of automation systems for freight vehicles. Trucks driving close behind each other use less space on the road and will result in a higher road capacity. Especially on busy roads with a lot of freight traffic, truck platooning may have a positive effect, as platooning trucks smooth the traffic flow. The studies also show that cooperation, even with a low penetration rate, may smooth the traffic flow. However, due to the lack of multiple field tests on public roads, it is hard to determine the real consequence of CACC systems for trucks. Especially for platoons consisting of multiple trucks, one has to make sure that a disturbance or speed variation of the leading trucks does not amplify over the platoon.

Safety

As platooning trucks are able to break immediately, without any reaction time, safety may be increased significantly. Moreover, since most traffic accidents occur due to human failure, it can be expected that automation will increase safety (Copsey, 2010).

Road load

Extra degradation of road infrastructure may be a result of truck platooning. When multiple trucks are driving close behind each other, road loads may be heavier and infrastructure damages may occur. Tests should prove what effect truck platooning has on road degradation and whether roads are able to cope with higher loads.

Engine heating

Engine heating is mentioned by Janssen et al. (2015) as potential barrier for the deployment of truck platooning. Less air is available to cool the engine for the following trucks. However, this consequence is expected to be small, because also less power is needed for the following trucks.

2.2.2. Assessed consequences

These consequences are estimated with modelling or pilot projects, the actual consequence is however not yet determined because truck platooning is not yet implemented in the real world.

Fuel consumption

A reduction of fuel consumption is one of the major benefits for vehicles driving in an platoon. Both leading vehicle and following vehicles experience a lower air drag. Numerous studies (both theoretical and practical) tried to determine the aerodynamic benefits of driving in a platoon (Alam et al., 2015; Lammert et al., 2014; Robinson et al., 2010; Bonnet and Fritz, 2000; Zabat et al., 1995). Depending on various factors maximum reductions between 7% and 25% in fuel consumption were found for following vehicles in a platoon. The leading vehicle generally experiences lower reductions. Findings of the different authors are summarized in Table 2.4.

Source	Findings for consumption	Potential fuel savings
Zabat et al. (1995)	Relation distance and drag	
Bonnet and Fritz (2000)	Influence of spacing and velocity	4.5 - 21 %
Robinson et al. (2010)	Influence of spacing and velocity	2 - 13 %
Lammert et al. (2014)	Influence of spacing, mass and velocity	5.3 - 9.7 %
Alam et al. (2015)	Savings for less ideal circumstances	6 %

Table 2.4: Savings in fuel consumption found by different sources.

The resistance on a vehicle driving with constant speed is the sum of the air drag force and the roll drag force. Air drag force (N) can be determined with the following equation:

$$F_d = 0.5 \times \rho \times v^2 \times C_d \times A \tag{2.1}$$

In which ρ (kg/m^3) is the density of the air, v (m/s) the velocity of the vehicle, C_d (-) the air drag coefficient and A (m^2) the cross sectional area of the vehicle. To reduce the air drag force one can reduce the vehicle velocity or its cross sectional area. Reducing these parameters is however often not economically viable. The air drag coefficient Cd is dependent on detailed shape of the vehicle and its positioning with respect to other vehicles. Truck platooning leads to a lower fuel consumption because it reduces the air drag coefficient. Note that next to the air drag force also the roll drag force plays a role in fuel consumption. Figure 2.2 shows the air profile around two platooning trucks. Both trucks experience a less beneficial profile for larger inter vehicle spacings. Note for example that for the smallest spacing no turbulent wake is developed in the flow pattern behind the leading truck.

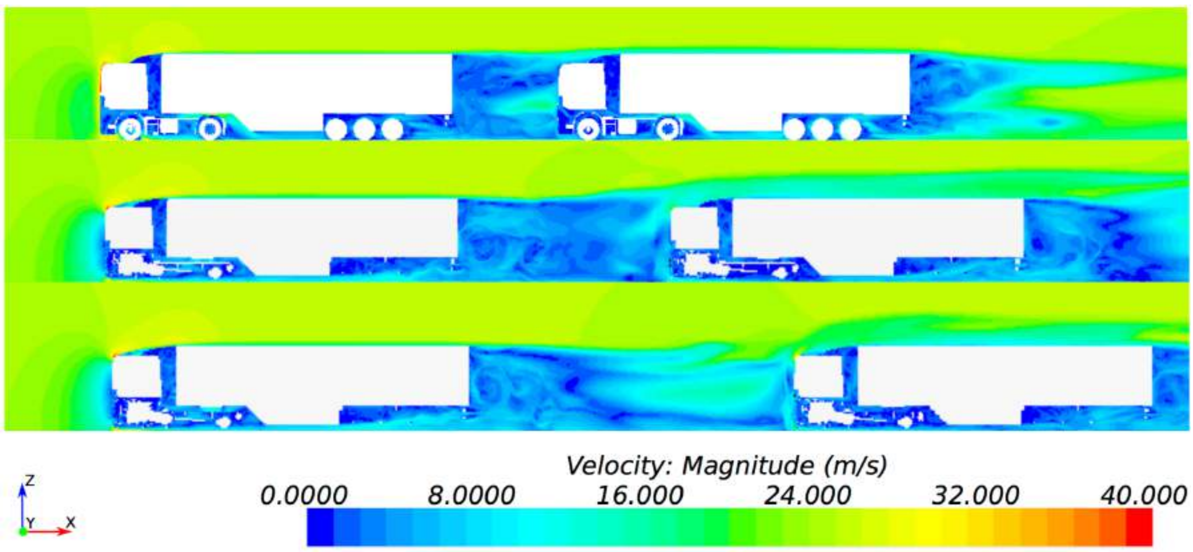


Figure 2.2: Wind speed around two platooning trucks with different spacings, calculated with computational fluid dynamics. Source: Alam, 2014.

Bonnet and Fritz (2000) wrote down the findings of the PROMOTE-CHAUFFEUR project in which tests were done with two trucks in platoon formation. Experiments were done on a test track under nearly ideal environmental conditions. For a spacing of 10 meter and a velocity of 80 km/h fuel savings of about 21% for the following truck and 6% for the leading truck were found. A platoon with a velocity of 60 km/h resulted in savings of 16% and 4.5% for respectively the following and leading vehicle. Larger spacing between the vehicles resulted in lower fuel savings.

Robinson et al. (2010) describes the findings of the SARTRE platoon project where a platoon of two trucks was formed. By means of simulation it was found that the air drag coefficient could decrease up to 50% for the following truck and up to 20% for the leading truck. Note that a decrease in air drag coefficient is not similar to a decrease in fuel consumption. Practical experiments were also performed in the SARTRE project. It was found that the fuel reduction of the following vehicle varies between 8 and 13%, while the reduction of the leading vehicle varies between 2 and 8%. Tests were done for a platoon driving with 90 km/h and vehicle spacing varying between 5 and 25 meter. Largest reductions were found for the smallest vehicle spacing. Note that the SARTRE project only performed tests with a platoon of two trucks. Fuel reductions will be greater for vehicles driving in the middle of a platoon since they benefit from air drag reduction as both following and leading vehicle. The efficiency of the leading vehicle will increase because closely following vehicles create a higher air pressure behind leading vehicles, see also Figure 2.2. Alam et al. (2015) reports on experiments with a platoon of three trucks driving. Compared to the previous described test, the experiments were conducted in less ideal circumstances, e.g. roads with slopes between -3 and +3% were used.

Reduction of emissions

The implementation of truck platooning will lead to a reduction in fuel consumption. Since emissions are directly related to the volume of fuel used, the technique of truck platooning will have positive environmental consequences.

Initial investment costs

New trucks equipped with platooning technology will be more expensive than regular trucks. Especially in the early stages of the implementation of truck platooning, these equipped trucks will be expensive. Janssen et al. (2015) estimates the extra technology costs at €10,000-2,000 per truck. However, these extra costs may vary a lot, dependent on truck brand, complexity of technology and competition between manufacturers.

2.3. Market characteristics

The technical characteristics and consequences of truck platooning are described in the previous sections. This section describes the market characteristics of truck platooning to get an idea which stakeholders may implement the technology for what reason (consequence). The truck platooning stakeholders are described, their relation with and view on truck platooning is analyzed with the push and pull principle.

2.3.1. Truck platooning stakeholders and their interests towards platooning

The stakeholders are identified to determine the playing field of truck platooning. A clear view on the interests of the different stakeholders is important to estimate the potential of platooning and to create an overview of the enablers and barriers of truck platooning. The users of platooning are carriers, shippers and truck drivers. The developers of the technology are the truck manufacturers, also called the Original Equipment Manufacturers (OEMs). Next to that, regulators and governments are identified as important stakeholders.

Carriers

The carriers are the companies that transport the actual goods and are therefore physically in charge of the transport. They are the owners of the equipment that is used for transporting the goods. Carriers may be interested in the truck platooning concept when this will drop their transportation costs. Early adopters of truck platooning may have a competitive advantage compared to other carriers. On the other hand, for optimal benefits carriers need to cooperate with each other to be better able to establish a platoon. This cooperation may be hard for the heavily competing carriers. Smaller carriers may only become interested in truck platooning when the number of platooning trucks becomes large and it becomes more easy to platoon with other trucks. Moreover, consequences of truck platooning need to become more clear before carriers want to adopt the technology.

Shippers

The shipper is the person or company that owns the goods. Most often the shipper uses a logistics service provider to transport its goods. It is therefore the party that tenders goods for transportation. As the shipper is the main customer of transport services, its power is rather large. They can for example oblige the carriers to make use of truck platoons, this can for example be based on environmental or financial reasons. Still, shippers need to know which freight flows are advantageous for truck platooning.

Drivers

Truck drivers are the final users of the truck platooning technology. They may have influence on the implementation of truck platooning. First of all, a future shortage of drivers may accelerate the implementation of platooning, because platooning gives the opportunity for unmanned trucks. This is especially the case for countries with high labor costs. Next to that, the role of the truck driver may change due to truck platooning. As drivers in following trucks do not need their attention on the road anymore, other tasks, like administrative work, can be performed while driving in a platoon. In this way, the efficiency of the truck drivers can be increased.

Regulator (national road authorities and legislators)

National Road Authorities (NRA) play a crucial role in the first implementation stages of truck platooning. As the technique of truck platooning looks promising and safe, the NRAs have to come up with new regulations regarding platooning. These regulations will be based on the impact of platooning on road capacity, the environment and the road safety. When regulation becomes too strict, for example due to extra restrictions for platoons, truck platooning may never become beneficial. Moreover, since truck platooning seems more interesting for longer distances, collaboration between different NRAs is needed to avoid extra costs for cross-border activities. Vehicle Authorities, such as the Dutch RDW, also play an important role for the implementation of truck platooning. They have to adapt their current assessment criteria to allow automated vehicles on public roads.

Truck manufacturers

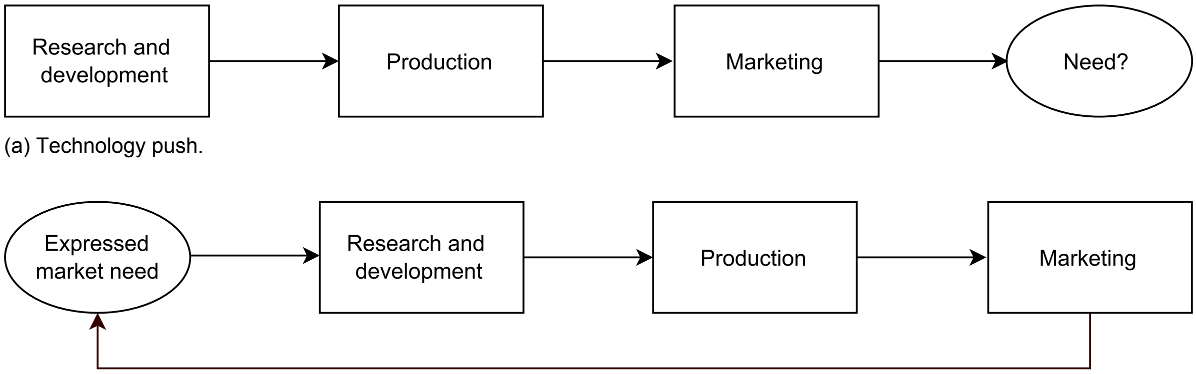
The major truck manufacturers, such as Scania, Volvo, MAN, Iveco, DAF and Daimler, are able to implement platooning techniques in their trucks. Several pilot projects and tests have been done, see Appendix A. Truck manufacturers are willing to invest in truck platooning as they want to benefit from the first mover advantages. The OEMs (Original Equipment Manufacturers) are therefore mainly responsible for the current technological push of the truck platooning concept. The current platooning systems of the above mentioned truck manufacturers are not able to cooperate. This could be a major problem for dynamic platoon formation. OEMs are responsible to come up with one standard platoon system to take the most advantages of truck platooning.

Governments and policymakers

Platooning of trucks may also result in several societal benefits, such as less congestion and less emissions. Governments may therefore act as facilitator of truck platooning by creating specific favorable boundary conditions. On the other hand, truck platooning may result in an unwanted reverse modal shift. For policymakers, it is important to know what impact platooning has on the modal split. They may take measures to avoid modal changes.

2.3.2. Technology push or market pull

To analyse the current perception of truck platooning, the concept is positioned in the push and pull principle. The different identified stakeholders are related to this push and pull principle. Figure 2.3 shows a theoretical representation of a technology push and a market pull. For a technology push the needs of a market are not considered before a technology is developed and pushed onto the market, this is showed in Figure 2.3a. Note that the market or potential need does not feedback the development of a new technology. The truck platooning concept can currently mainly be characterized as a technology and policy push. OEMs are investing in automated and cooperative technologies for vehicles. Also governments try to push the technology of truck platooning into the market. According to Martin (1994), a technology push can be found for innovations for which there is no manifest need. By pushing the innovation onto the market a latent need should become manifest.



(a) Technology push.

(b) Market pull.

Figure 2.3: Representation of the push and pull principle.
Source: Martin, 1994.

A representation of a market pull is given in Figure 2.3b. For the market pull situation a defined market need is present and this is an input for the R&D, production and sales functions. Potential market pull stakeholders for the truck platooning are shippers and carriers. The six important stakeholders, identified in this chapter, are represented in Figure 2.4. Their relation to each other is plotted to show which stakeholders fulfill the different tasks concerning truck platooning.

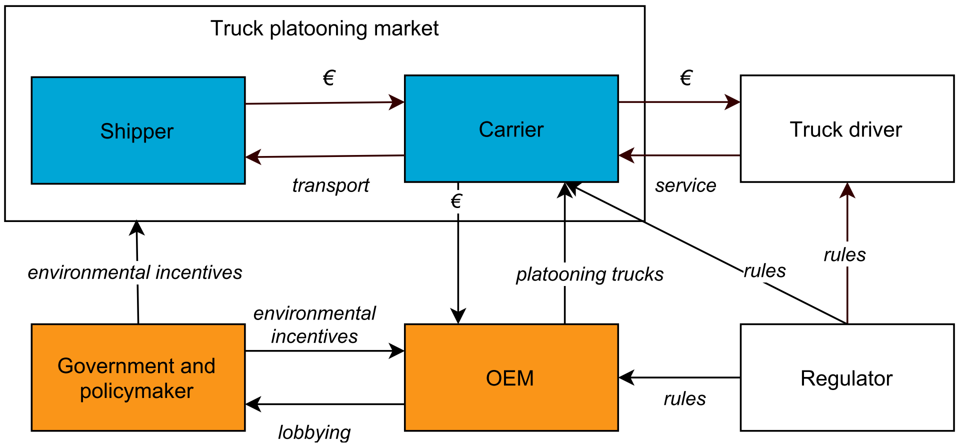


Figure 2.4: Identified stakeholders and their relation to each other. The orange stakeholders represent the technological and governmental push while the blue stakeholders represent the potential market pull.
Source: Partly based on Janssen et al. (2015).

Another representation of the technology push and the market pull for truck platooning is given in Figure 2.5. The hypothetical interests for both the market and the platooning developers are given over time. A large increase in interest for developers can be noticed after the first appearance of the technology. This peak in the public interest and technological push is actually happening in 2016, as the media pays attention to the concept and different truck platooning meetings or conferences are organized (Eckhardt, 2016). The current high interest or visibility of truck platooning is also visualized by the Gartner's 2015 hype cycle for emerging technologies (Burton and Walker, 2016). Autonomous vehicles shifted to the top of the curve in 2015. This means that the technology is at the peak of inflated expectations. Major cause of this peak is the attention of the car manufacturers, all major OEMs put autonomous cars on their near term roadmaps.

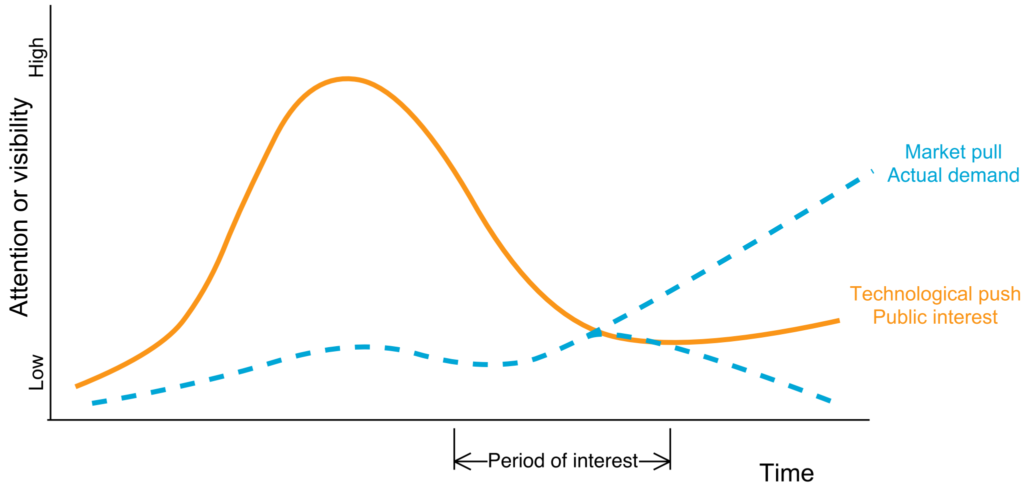


Figure 2.5: Hypothetical interest for the truck platooning concept for both the market and the developers.
Source: Partly based on the Gartner's hype cycle (Linden and Fenn, 2003).

Significant market pull or market demand may evolve in a later stage. The pull is plotted with a dotted blue line in Figure 2.5. Dependent on the success of the diffusion of the innovation, the pull may increase or decrease after the peak of the technological push. The period of interest of this thesis is just before this actual diffusion of truck platooning, since the objective of this thesis is to find out whether the transport market should adopt the platooning technology.

Note that Figure 2.5 shows hypothetical interests and that it is not sure whether and when the market is interested in the platooning technology. For optimal implementation, the crux however is to decrease the time between the development of the platooning concept and the actual implementation of platooning, this time is visualized as period of interest in the figure. Moreover, the question is whether the peak of the technology push is high enough to trigger the latent market pull in a later stage.

2.4. Conclusion

This chapter described the concept of truck platooning with its technical characteristics and its market characteristics. Two main conclusions can be identified. First of all, the concept of truck platooning seems to have large potential as the automation and cooperation of road freight transport goes along with beneficial impacts. However, the magnitude of the impacts is not yet defined and this makes it hard to estimate the actual potential of the concept. Next to that, the analysis of the truck platooning market showed that several large stakeholders with different interests need to cooperate to make truck platooning successful.

In general one can conclude that the implementation is and will be a difficult and complex process. This is mainly caused by the many uncertainties and different stakeholders. Based on the analysis in this chapter the first two research questions can be answered.

What are the characteristics of truck platooning as a transport mode?
Truck platooning encompasses the automation and cooperation of freight road transport. Automation and cooperation of trucks can be gradually expected over time and are both needed to gain the full potential of truck platooning. Automation of freight road transport may result in less transport costs and an increase in safety whereas cooperation of trucks may lead to less congestion as well as higher road safety.

Which needs in the transport sector can be fulfilled by the implementation of truck platooning?
Currently, truck platooning is mainly based on a technological push, as governments and truck manufacturers try to push the technology into the market rather. However, the market may become manifest when the expected and assessed consequences will be realized. Several needs can be fulfilled by truck platooning because the technology may decrease transport costs, increase safety and decrease congestion and pollution. Truck platooning may result in both societal and economical benefits.

3

Freight transport innovations; the perspective of truck platooning

Different innovations in freight transport are evaluated and enablers and barriers are identified. These enablers and barriers are related to the concept of truck platooning to determine the perspective of this technology. Based on the findings, developments that are critical to the implementation of the truck platooning technology can be indicated.

3.1. Measuring innovation

The term innovation is differently described by several authors (Rogers, 2003; Tidd et al., 2001; Van de Ven et al., 1999). Generally, innovation is related to change of a certain existing product or process. As mentioned by Van de Ven et al. (1999), innovations occurs after development and implementation of an idea. The success of an innovation depends on the adoption or diffusion of the innovation.

Many successful inventions fail to become innovations, even when well planned (Tidd et al., 2001). This might also be the case for truck platooning because currently, truck platooning is still an invention. To become a real innovation, the technique should be successfully implemented and therefore it should be used by the market. Measuring innovation or determining the success of an invention depends on a lot of factors. Moreover, the implementation of an innovation does not only relate to the performance of the innovative product or service, but also relates to several external factors (Tidd et al., 2001).

3.1.1. Indicators for the adoption of an innovation

Much literature about the diffusion and adoption of innovations is available (Greenhalgh et al., 2005). However, only few literature exists on freight transport innovations and their potential implementation (Van Binsbergen et al., 2014). To measure whether a successful invention becomes an innovation different indicators are chosen to find enablers and barriers of an innovation. Many different methods have been used to evaluate the adoption and diffusion of innovations. Greenhalgh et al. (2004) evaluated publications on the diffusion of innovations with a meta-review. This review found several indicators of innovations and in general these indicators are in line with the innovation product characteristics of Rogers (2003). Therefore the product characteristics of Rogers (2003) are used in this chapter to evaluate different transport innovations. These product characteristics are part of the technology push described in the previous chapter. Although the product characteristics of Rogers (2003) were initially based on consumers, they are also widely used to analyse other innovations and markets. Examples can be found in the transport innovation analyses of Van Binsbergen et al. (2014) and Visser et al. (2008). Next to these product characteristics, user requirements are evaluated to find potential barriers and enablers of innovations. These user requirements are discussed to evaluate the importance of the market pull of an innovation. Finally, several external factors are discussed because these may also have a major impact on the adoption of an innovation (Tidd et al., 2001).

3.1.2. Framework for finding barriers and enablers of an innovation

The framework used in this chapter is presented in Figure 3.1 and distinguishes three different areas; product characteristics, user requirements and external factors.

The enablers and barriers concerning the product characteristics can be found by evaluating four different indicators; simplicity, observability, compatibility and trialability. These indicators are identified by Rogers (2003) as the characteristics that affect the diffusion of an innovation. When the indicators or characteristics are perceived as being better than the existing technological dimensions, then they can be perceived as enablers rather than as barriers for adoption. Rogers (2003) also mentions relative advantage as an indicator. A relative advantage is the degree to which an innovation performs better than the existing technology or mode. For this research such a relative advantage is captured in the user requirements.

The following product characteristics are discussed:

- Simplicity; relates to the easiness of the innovations, its development and its understanding. A complex innovation is often less likely to be adopted.
- Observability; the degree to which the innovation is visible to others. An innovation is more likely to diffuse when the benefits are visible.
- Compatibility; to which degree does the transport innovation fits with the current and existing technologies and modes. Enablers can be found when the transport innovations makes use of existing infrastructure or existing equipment.
- Trialability; to which degree is the innovation tested and experienced. This is measured in pilot projects and real life cases and shows less uncertainty to potential adopters and allows learning by doing. Innovations which can be trialed will generally be adopted more quickly than those which cannot.

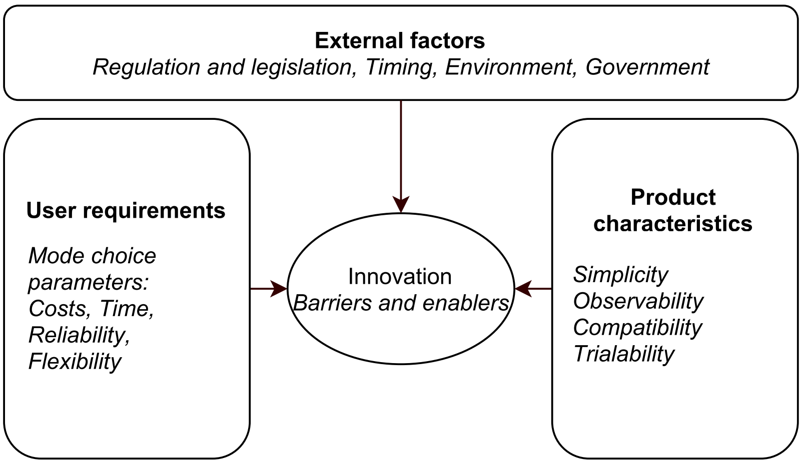


Figure 3.1: Theorectical framework for the identification of enablers and barriers of innovations in the transport sector.
Source: Based on Van Binsbergen et al. (2014); Visser et al. (2008); Van der Straten et al. (2007); Rogers (2003); Tidd et al. (2001).

According to Tidd et al. (2001) external factors may play an important role in the diffusion of an innovation. Different external factors will be addressed to find barriers and enablers for different transport innovations. External factors may for example consist of the role of the government, existing regulation or the timing of an innovation. Especially when an innovation results in societal benefits, external factors as interference of governments or legislation are important. For example, governments can be involved in different ways and enable an innovation by facilitating, initiating or coordinating. Barriers can be imposed by legal restrictions or other financial measures.

The actual users of transport innovations are the shippers and carriers, as described in the stakeholder evaluation. Therefore, the user requirements are based on the mode choice parameters that are used in the transport and logistics sectors. Important mode choice parameters are transportation costs, reliability, speed and safety (Rodrigue et al., 2013). Other sources refer to these factors as the operationalization of relative advantages (Van Binsbergen et al., 2014; Visser et al., 2008).

3.2. Transport innovations

Five different freight transport innovations are selected and evaluated with the framework in Figure 3.1 to find the enablers and barriers that made the innovations successful or unsuccessful. The evaluation is based on literature and personal communication. The selected innovations are chosen because they have to some extend similarities with the truck platooning concept. Especially infrastructure usage and automation are two parameters that make the truck platooning concept unique. The five selected innovations show similarities on at least one of these parameters. Figure 3.2 shows the innovations with their degree of automation and the need of dedicated infrastructure. Freight transport innovations often show improvement on one of these parameters. Unique about truck platooning is that automation is involved and it uses existing infrastructure.

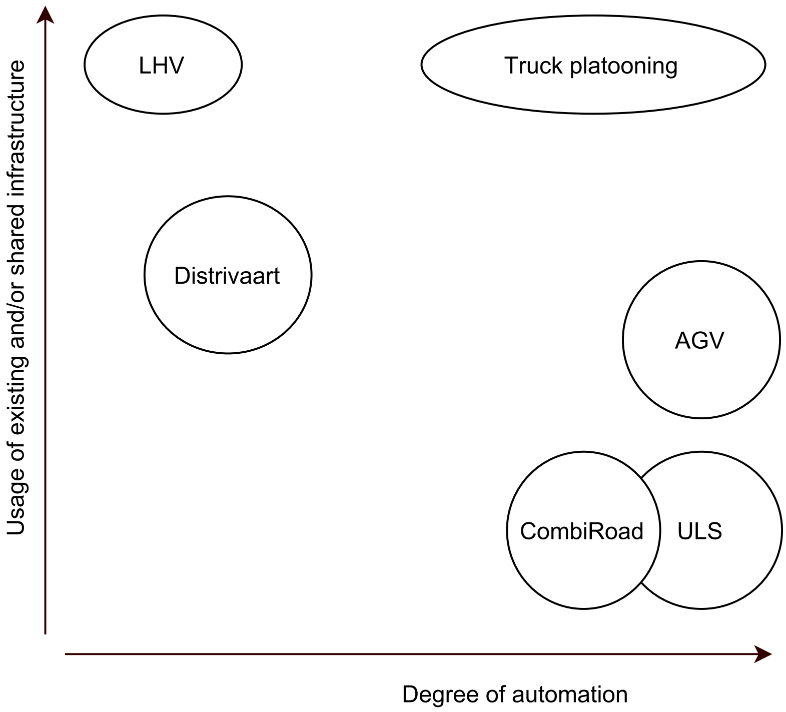


Figure 3.2: Different freight transport innovations and their degree of automation and usage of dedicated infrastructure. Source: Based on Janssen et al. (2015); Vos (2015); Kindt et al. (2010); Visser et al. (2008, 2007).

3.2.1. Automated guided vehicles

Several large container terminals make use of automated guided vehicles (AGV) for intra terminal transport (Rodrigue et al., 2013). The Delta Sealand terminal in the Port of Rotterdam was the first terminal that used AGVs for transporting containers (Duinkerken and Terstegge, 2001). See Figure 3.3a for the AGVs that are used at the Maasvlakte 2 in Rotterdam. The automated vehicles were introduced in 1993 and were part of the first automated terminal. The introduction of AGV and truck platooning have in common that both innovations concern automation of road freight transport.

Adoption and advantages

Efficiency and transshipment costs are important indicators for container terminals (OECD, 2014). Especially in countries with high labor costs, automation may lead to a significant competitive advantage. Therefore, the relative advantage of implementing AGVs is a reduction in labour costs. Moreover, since no drivers are needed at the terminal anymore, the safety increases (Vos, 2015). Another aspect that can be perceived as enabler is the usage of infrastructure. AGVs drive on dedicated infrastructure, this makes the automation of vehicles more simple, i.e. the automated vehicles only have to communicate with each other and the infrastructure. Moreover, normally the infrastructure is already available and this makes the innovation compatible. Though, the used infrastructure is not shared with other users and therefore the automation of these vehicles is less complex. Rodrigue et al. (2013) state that automated terminals are in general more productive and competitive than traditional terminals. Still, the majority of container terminals does not use AGVs yet and therefore one can conclude that the adoption develops rather slow.

Diffusion

After the successful implementation of the AGVs at the Delta Sealand terminal, it took nine years before a next terminal adopted the technology. The CTA terminal in Hamburg introduced AGVs in 2002 (Yang and Shen, 2013). Similar to truck platooning, the Netherlands or the Port of Rotterdam serves as a stepping stone for developing and implementing new technologies. Other terminals face some barriers and postponed the introduction of AGVs. First of all, the adoption of AGVs involves higher initial investment costs. Especially the transition from a traditional terminal to a more automated terminal is expensive. Next to that, an external factor or barrier that plays an important role in the diffusion of AGVs is the high reduction in jobs due to automation in combination with the large power of labor unions (Beškovnik, 2008). One can conclude that although the adoption of AGVs on container terminals results in various advantages, the diffusion of the concept is rather slow due to several barriers. However, a strong market pull for automation on terminals can be noticed due to the competition between terminals. This resulted in numerous studies and inventions on this topic (OECD, 2014).

(a) AGVs at the APM terminal, Maasvlakte 2, Netherlands.

(b) LHV combination driving on Dutch highway.

Figure 3.3: Freight transport innovations successfully implemented in practice.
Sources: Kindt et al., 2010; Tazelaar, 2014.

3.2.2. Longer heavier freight vehicles

Longer heavier freight vehicles (LHVs) are commonly referred to as road freight vehicles that are longer and may be heavier loaded than the European guidelines prescribe (Kindt et al., 2010). LHVs can be created by combining different existing truck, tractor and trailer configurations. An example of a LHV combination is showed in Figure 3.3b. Where Sweden and Finland have a long tradition with LHVs, there are several restrictions for LHVs in other European countries (Christidis and Leduc, 2009). The Netherlands started a trial period with LHVs in 2001 and Dutch regulation allowed LHVs some years later officially (Aarts and Salet, 2012).

The Netherlands allowed road vehicles with a length of 25.25 instead of 18.75 meter and a weight of 60 tons instead of 50 tons (Hagen et al., 2006). This directly means that more freight can be transported by a single driver. For example a single road combination can transport 3 TEU instead of 2 TEU. Moreover, it is more efficient in terms of fuel and emissions to transport larger batches. Trial projects showed that the implementation of LHVs results in fuel consumption savings of more than 10% (Kindt et al., 2010). The LHV innovation has a lot of common advantages with the concept of truck platooning. The implementation of both innovations may result in less fuel consumption, road optimization and an increase in driver efficiency. Moreover, both innovations mainly replace regular road trucks and use existing road infrastructure.

Regulated adoption

The adoption or diffusion of the LHV in the Netherlands is well documented. The Dutch government insisted that the allowance of LHVs would not lead to a reverse modal shift or more unsafe roads (Hagen et al., 2006). Therefore, different pilot projects were conducted and strict guidelines for the implementation were set. To use LHVs a carrier was obliged to apply for an exemption at the Dutch National Road traffic Department (RDW). The LHVs were only allowed to drive at certain established routes and the drivers had to take extra exams to drive the LHV combinations. Moreover, some restrictions to weather conditions and load were made (Aarts and Salet, 2012). This strict legal framework around the LHVs in the Netherlands may be perceived as a barrier for the adoption of the innovation. Especially in the first few years after the introduction of the concept in the Netherlands, only a very small number of companies adopted the technology (Kindt et al., 2010). After some trial projects the regulation eased (i.e. more corridors became available) and more companies started to adopt LHV combinations, see also Figure 3.4.

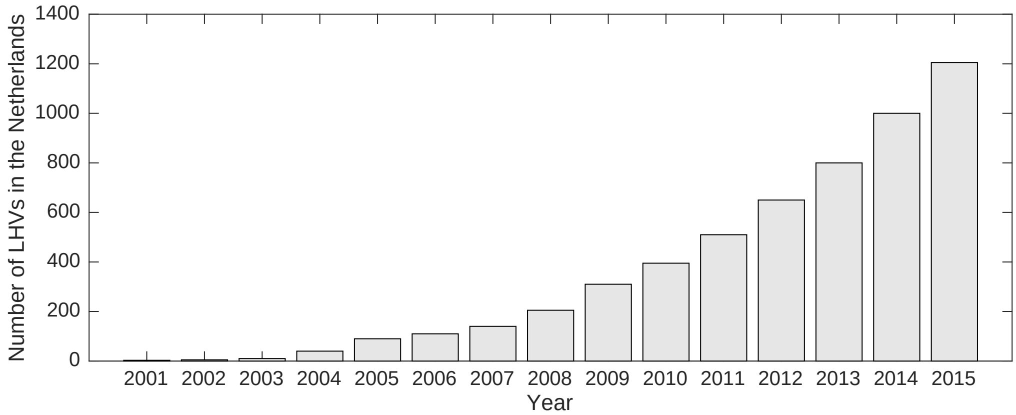


Figure 3.4: Number of LHVs that are registered in the Netherlands plotted against the time.
Sources: Aarts, 2016; Van Aartrijk, 2015; Aarts and Salet, 2012; Kindt et al., 2010.

Over the last 15 years an increase in LHVs in the Netherlands can be noticed. Still the penetration rate of LHVs is rather small, since less than 1% of the road freight vehicle kilometers in the Netherlands was travelled with a LHV in 2015 (CBS, 2016a). Aarts (2016) mentioned that the penetration rate of LHVs in the Netherlands will not increase rapidly in the near future and that no major growth is expected under the current circumstances and regulations.

Reverse modal shift

Kindt et al. (2011) evaluated the observed and potential reverse modal shift due to the adoption of the LHVs in the Netherlands. Although LHVs result in a more efficient way of freight traffic no modal shift from barge and rail to road was noticed. Only regular truck journeys are replaced by LHVs. Some reasons for this unchanged modal split can be indicated:

- LHVs were not allowed in neighbouring countries; Belgium and Germany. The first LHVs trips were made in 2015 and 2012 in Belgium and Germany respectively. And currently hardly any LHVs can be found in these countries because the regulation is strict. Due to transshipment costs, intermodal transport becomes increasingly beneficial for larger distances. So, LHVs are not able to replace cross-border transport of goods.

- For bulk commodities, that are mainly transported by barge or rail, LHVs will weigh more that 60 tons when fully loaded. Therefore, it becomes less efficient to transport these commodities with LHVs (Aarts and Salet, 2012).
- LHVs are not able to transport forty foot containers more efficiently than regular trucks. The major part of containers that need to be shipped from the Port of Rotterdam to the hinterland are forty foot containers (Kindt et al., 2011). Like a regular truck-trailer combination, a LHV can only transport one forty foot container.

It can be expected that the adoption of LHVs in other countries may result in a reverse modal shift. The concept becomes more interesting when also cross-border journeys are allowed. LHVs become more competitive with other modes when longer distances can be covered. Moreover, in countries where rail transport has a large share in the modal split, road transport will be more competing due to the lower costs of LHVs (Aarts and Salet, 2012). Therefore, Bergqvist and Behrends (2011) propose to allow LHVs for pre- and end haulages only. It is argued that intermodal transport becomes especially expensive due to its high pre and end haulage costs. When LHVs are only allowed for intermodal transport, a shift from road to rail is even more likely to happen. Bergqvist and Behrends (2011) found out that this new policy regarding intermodal transport may result in a 5-10% reduction of transport costs for the shipper that uses intermodal transport.

Major enablers

Less emissions, less fuel consumption and less labour costs gives the LHV innovation more beneficial mode choice parameters compared to its predecessor; regular trucks. Moreover, no extra or new infrastructure is needed for the implementation and that makes the innovation compatible with existing technologies. These enablers also hold for the concept of truck platooning, they however do not directly result in a successful adoptation. As mentioned above, less than 1% of the road freight kilometers is travelled by LHVs. The compatibility of LHVs may even be perceived larger than the compatibility of truck platooning because LHV combinations can be created with existing equipment. Carriers do not need to buy new trucks or trailers to adopt the technology. Finally, one can conclude that the legal framework has a major influence on the adoptation of LHVs.

Predicting adoption

Several studies were done to predict the impact and the adoption rate of LHVs in the Netherlands (Rosenberg and Lieshout, 2005; NEA, 1997). The predicted adoption rate was determined by analyzing the potential markets, distances and commodities for LHVs. Next to that, different implementation scenarios are evaluated. Important parameters for these scenarios are weight of the LHV and available infrastructure. Although detailed analyses were done, one can conclude that an accurate prediction of the adoption rate is hard. For example, Rosenberg and Lieshout (2005) estimated an adoption rate of at least 9%, whereas currently only an adoption rate of 1% can be found.

Recently, LHVs are also allowed in Germany. The first public road tests with LHVs in Germany were done in 2012 and in 2015 around 100 LHVs are registered in Germany (Irzik, 2015). The German government recognizes the large benefits of LHVs, still the adoption is rather slow. Main barrier in Germany is the large power and lobby of the German rail companies (Irzik, 2015; Van Aartrijk, 2015). They fear a reverse modal shift and try to stop the implementation of LHVs.

3.2.3. Underground logistics system

The underground logistics system (ULS) is a network of underground tubes that provides fast and frequent transport of freight by automated vehicles (Van der Haagen, 2000). The concept can be ideally used for congested areas that need frequent freight transport, e.g. urban freight transport or inter terminal transport. The ULS concept is evaluated in this research because the innovation has some similarities with the concept of truck platooning. Moreover, although studies showed that the implementation of ULS could be feasible, real adoption of the ULS concept has never occurred (Visser et al., 2008; Van der Haagen, 2000; Maas, 1997). Visser et al. (2008) reviewed the ULS in the Netherlands and found enablers and barriers with a comparable framework as used in this research, see Figure 3.2. The following evaluation is mainly based on the findings of this review.

Benefits of the concept

The development of the ULS concept already started in 1970. From this point on, several researches and projects about ULS were performed (Visser, 1999). A lot of these projects were funded by governmental resources and therefore governmental push can be noticed. Although a real ULS was never constructed, the many pilot projects can be perceived as an enabler for the ULS concept. Main benefit of an underground logistics system is that is able to transport goods on a fast and frequent basis without disturbance by any other transport mode. Moreover, the dedicated infrastructure makes the implementation of an automated system less complex. As mentioned by Visser et al. (2008), the implementation of ULS would be innovative, but based on a proven technology.

Implementation failure

It was concluded that the main barrier or major cause of the implementation failure is compatibility (Visser et al., 2008). This compatibility issue can be explained in two perspectives. First of all, an ULS needs new and dedicated infrastructure. Next to the fact that underground infrastructure is expensive, it is also not clear who has to pay for the infrastructure. Private companies are normally not used to pay for infrastructure and sufficient political support for governmental financing of the infrastructure was lacking (Visser et al., 2008). Secondly, compatibility is perceived as a barrier because the transportation with ULS needs extra transshipment. No door-to-door transport is possible with the ULS and therefore transport by trucks may be less expensive. Moreover, for trucks the infrastructural costs are often not payed by the shipper and therefore this mode is perceived as cheaper. Finally, the lack of a real problem owner is a notable external factor that is perceived as a barrier. No actor had the responsibility of a successful implementation and no real driving force was present.

3.2.4. CombiRoad

In 1994 a public-private partnership was created between the Dutch government and several freight transport companies for the development of CombiRoad. This system focuses on freight transport with automated vehicles (Visser et al., 2007). Electric and automated trucks drive with a speed of 50 km/h on dedicated tracks. The main goal was to develop a system that was able to transport large volumes of goods between the port of Rotterdam and inland terminals (Konings et al., 2005). For the system, some relative advantages compared to rail freight transport can be noticed. The rubber tyres of the automated trucks result in less noise. Next to that, transshipment of for example containers from road trucks to the CombiRoad system is relatively easy and efficient. An automated tractor can replace the regular tractor and the load can stay in the trailer. Moreover, other relative advantages compared to regular road transport can be noticed. The dedicated track results in more reliability due to less congestion and more safety.

Implementation failure

The CombiRoad system was successfully tested on a short track in the Netherlands. Therefore, the system proved to be technically feasible (Konings et al., 2005). However, an actual implementation of CombiRoad was never achieved. Several implementation barriers can be addressed. Probably the largest barrier was the expected modal shift from rail to CombiRoad. For the proposed route, the Betuweroute, the government had to chose between investing in rail infrastructure or CombiRoad infrastructure. The Dutch government chose to invest in rail infrastructure because the CombiRoad system did not prove its profitability on a larger scale. For this reason, compatibility and trialability can be identified as barriers for the CombiRoad concept.

3.2.5. Distrivaart

Distrivaart is a system that offers the possibility to efficiently transport palletized goods with barges at inland waterways. The innovation aimed for frequent flows of cargo between distribution centers and producers (Iding, 2004).

Market potential

Generally, bulk goods and containers are transported by barge. The Distrivaart innovation focuses on other goods that have a higher time value and consist of smaller quantities. In other words, Distrivaart tries to target on fast moving consumer goods. Therefore, this innovation may be able to enlarge the market of inland waterway shipping. Wiegmans (2005) evaluated several innovations for barge transport and mentions that only Distrivaart and some other innovations try to enlarge the market. Such innovations may create a modal shift from road to inland waterway and may therefore result in less road congestion and emission.

Distrivaart is related to truck platooning because the potential freight flows may be similar in the first stages of the implementation of the platooning concept. Frequent cargo flows between distribution centers could be ideal for the first implementation of truck platooning. These flows have large volumes and a large share of the routes is travelled on highways. Moreover, a a potential barrier is avoided, i.e. no cross-border routes need to be travelled and this results in less pressure on international legislation.

Implementation failure

Although promising, the Distrivaart concept is not yet adopted. Wiegmans (2005) mentions relative high investment costs as a weakness or barrier of the concept. Moreover, another important barrier for Distrivaart is the decrease in flexibility (Iding, 2004). Transporting larger batches results in less flexibility for the shipper, e.g. once goods are loaded on a barge their destination can not be changed. Next to that, the distribution centers need to be able to handle large quantities at once. This negative effect also holds for the truck platooning concept, as two or more trucks arrive at the same time. This results in more variability for cargo handling and distribution centers.

Iding (2004) mentions that a larger financial contribution of governments may have resulted in a successful implementation of Distrivaart. Private parties invested more in the project than governmental organizations. This was noticeable due to the potential positive societal effects of the innovations, i.e. less road congestion and less emissions. Though, it is not a primary governmental task to finance innovations as Distrivaart and other barriers largely contributed to the implementation failure. For example, Iding (2004) concludes that the implementation of Distrivaart was hard because it was only advantageous when the entire network is involved. An economic study showed that the Distrivaart project was feasible when the weekly demand was at least 650 pallets (Groothedde and Rustenburg, 2003). Initially, this requirement could be easily met when all stakeholders participated in the project. However, before the implementation was realized a big stakeholder left the Distrivaart project and the project was no longer economically feasible (Van Binsbergen et al., 2014). One can conclude that a project or innovation may become a failure when the cooperation between different users is essential and it is easy for a single user to quit. Moreover, small scale pilots are hard to realize when a critical mass is needed for a feasible implementation. This may also be the case for the truck platooning concept, since platooning is more beneficial when more trucks or parties are involved.

3.3. Potential enablers and barriers for the implementation of truck platooning

In the previous sections several innovations that are related to truck platooning are discussed and evaluated based on the defined framework, see Figure 3.1. This section discusses the enablers and barriers that are found in the analysis above and are applicable for the concept of truck platooning.

3.3.1. Relation between selected innovations and truck platooning

The potential enablers and barriers for truck platooning and their influence are summarized in Table 3.1 and 3.2. The influences are categorized in three levels, i.e. high, medium and low. These influence levels show the effect or impact that a certain enabler or barrier has on the adoption of the reference transport innovation. The levels are based on the descriptions of each transport innovation. Note that this influence level is not necessarily similar for the truck platooning concept. The indicator column shows the position of the different enablers and barriers in the used framework.

Enabler	Indicator	Reference	Influence
Use of existing infrastructure	Compatibility	LHV, AGV	High
Larger truck driver productivity	User requirements	LHV, AGV, CombiRoad, ULS	High
Governmental support	External factor	LHV	High
Lower fuel consumption and less emissions	User requirements	LHV	Medium
Several pilot projects show potential	Observability, trialability	LHV, CombiRoad	Medium
Infrastructure capacity increase	User requirements	LHV, Distrivaart	Medium
Increase in road safety	User requirements	AGV	Low

Table 3.1: The enablers of truck platooning and the relation with the theoretical innovation framework. The influences are based on the reference innovations.

Barrier	Indicator	Reference	Influence
Legal restrictions	External factor	LHV	High
Power of competitors	External factor	LHV, AGV	High
Critical mass needed for implementation	Compatibility, external factor	Distrivaart	High
Bundling of goods	User requirements	Distrivaart, LHV, CombiRoad	High
No support of unions	External factor	AGV, LHV	Medium
Potential reverse modal shift	External factor	LHV, CombiRoad	Medium
Cooperation needed between shippers	Compatibility, user requirements	Distrivaart	Medium
Many stakeholders with conflicting interests	External factor	ULS, CombiRoad, Distrivaart	Medium
Cross-border transport not possible	Compatibility, external factor	LHV	Medium
No problem owner	External factor	ULS	Medium
Predefined routes	Compatibility	LHV	Low
Extra driving skills needed	Compatibility	LHV	Low

Table 3.2: The barriers of truck platooning and the relation with the theoretical innovation framework. The influences are based on the reference innovations.

3.3.2. Review of enablers for truck platooning

Product characteristics

At the early stages of the implementation of truck platooning, legislation will probably require at least one driver in every truck in a platoon. In this case, a lower fuel consumption and its corresponding lower environmental impact can be regarded as the main enablers. Fuel consumption savings are perceived as an important enabler for the technology. As explained in Section 2.2.2, the savings are expected to be around 10% in beneficial circumstances. However, no test results for real life cases exist and pilot projects are needed to find the actual savings of truck platooning. The fuel saving benefits of truck platooning can be compared with the benefits of LHVs. Longer heavier freight vehicles have a realized fuel consumption benefit of around 10% (Kindt et al., 2010). However, at first sight, the implementation of LHVs seems easier and cheaper, because LHVs are using existing technology and equipment. Therefore, it is likely that other enablers are needed for a successful implementation of truck platooning. Next to that, from the LHV case it can be concluded that several other enablers and barriers play a major role in the adoption of an innovation, such as the legal restrictions.

External factors

From the above described analysis it can be concluded that governments often play a major role in the development and adoption of transport innovations (Van Binsbergen et al., 2014; Konings et al., 2005; Iding, 2004). The current role of governments towards the truck platooning concept can be perceived as an enabler. Especially the Dutch government invests in the concept. For example, Rijkswaterstaat, a governmental agency in the Netherlands, organized the EU Truck platooning challenge in 2016. This event showed the possibilities for cross-border transport with platooning trucks. Moreover, in 2016 the European Commission granted financial support for the development of multibrand platooning. It is however uncertain what the role and viewpoint of the governments will be in the future and during the adoption. Governments can enhance the implementation by creating dedicated lanes for automated vehicles or by granting subsidies for companies that use platooning technologies. On the contrary, governments may also slow down the implementation. For example, when a truck platooning results in a reverse modal shift, the stricter legal framework can create a barrier. The question arises whether governmental support is really needed for the adoption of truck platooning or if the support only accelerates the adoption. Moreover, governmental support is hard to justify when the societal benefits of truck platooning are unknown.

User requirements

Automation and its corresponding enablers will probably have a high impact on the adoption of truck platooning. The concept is unique in a sense that automation is combined with existing public infrastructure. Possible enablers of truck automation are less personnel costs and a potential higher trip distance without resting of drivers. As can be concluded from the AGV and LHV cases, less personnel may be a main enabler for the adoption of an innovation. For these cases, less drivers can be clearly viewed as an user requirement for carriers. Especially for the AGV case, the high personnel costs in Northwestern Europe are an important enabler for automation. Longer distances can be covered with platoons of trucks when the legal framework allows for longer driving times. The productivity of the drivers becomes higher and platooning trucks will be more competitive with long distance rail transport.

Based on the cases of CombiRoad and ULS one can conclude that the usage of existing infrastructure is a major enabler for the adoption of an innovation. The construction of new infrastructure is in most cases expensive (Konings et al., 2005; Maas, 1997) and it is often not clear who is responsible for the new infrastructure and its construction and maintenance. Truck platoons make use of existing infrastructure and therefore have a competitive advantage with CombiRoad and ULS. Even when dedicated lanes are constructed for automated vehicles, existing infrastructure can be used.

It is not yet determined if or to what extent the implementation of truck platooning improves the safety of road transport. Pilot tests are needed to determine the impact of platooning trucks on traffic safety. However, the general perception is that automation makes vehicles more safe. Therefore, it is fair to assume that safety will be perceived as an enabler.

3.3.3. Review of barriers for truck platooning

Product characteristics

A major barrier for the adoption of truck platooning is the fact that cooperation is needed between competing industries and companies. First, collaboration between different OEMs to make multibrand truck platooning available. Second, cooperation between different carriers to establish the actual platoons on the road is needed. Third, cooperation between national road authorities is needed to allow cross-border transport of platoons. As was found in the Distrivaart case sometimes cooperation is crucial for the implementation of a new transport concept. Even when a positive business case is created a concept can fail when a stakeholder withdraws.

Truck platooning becomes more beneficial when more trucks are able to platoon. Therefore, no or little first movers advantages is present. This threshold to enter the truck platooning market may be perceived as a major barrier. Next to that, when multiple carriers cooperate to establish a platoon, the benefits of platooning need to be distributed over the different carriers. This could be a complex task since not all the trucks in a platoon benefit equally and not all trucks drive the same distance.

To prove the concept in truck platooning in practice still a lot of pilot projects are needed. As was found in the cases described in the previous sections, observability and trialability are important indicators. These indicators relate to the number of successful pilot projects. However, for truck platooning it is not clear who is responsible for these pilots and who is willing to finance or contribute.

User requirements

The trucks drivers and their acceptance towards the truck platooning concept may play a major role in the implementation of the concept. The acceptance or platooning experience of the drives is dependent on the spacing between the trucks in the platoon, this can vary between 0.3 and 1 second. Below 0.5 second drivers may feel unsafe and really need to get used to the system. This is especially the case when following drivers do not know the driver in the leading truck. Based on personal communication with truck drivers not much extra training is needed for the drivers, but this is mainly based on test drivers that know the system very well (Scania, 2016). Other drivers that were used in a platoon do not think that platooning is very much different from well known systems as ACC. Therefore the drivers perception can also be an enabler. However, no pilot tests with spacings below 0.5 seconds were performed.

Finally, an important barrier can be noticed in the time loss that may be caused by the formation of a platoon. When the density of platooning trucks is low, significant formation times to create platoons may arise. Potential adopters of the technology may be discouraged due to these platoon formation times.

3.4. Critical developments for the adoption of truck platooning

Based on the analysis of the related freight transport innovations in Section 3.2 and the review of the enablers and barriers for the concept of truck platooning in Section 3.3, some critical steps or developments for a successful implementation and adoption of truck platooning can be identified. The developments are verified with expects and are summed up below:

- Essential for the successful implementation of truck platooning is the possibility of cross-border transport (Smit, 2016). Truck platooning becomes more interesting for longer distances and also the LHV case showed that the market is limited when no cross-border transport is allowed. Collaboration between EU member states is therefore needed.
- The possibility to platoon with different trucks or multibrand platooning is needed for successful dynamic formation. The opportunity to platoon with other (unknown) carriers will increase significantly. A general platooning system or technique should be created and adopted.
- The benefits of platooning need to be fairly distributed amongst the truck platooning users. This is especially the case for dynamic platoon formation. Otherwise, a leading truck will have less benefits than a following truck. Carriers mentioned that a third party with a role as platooning service provider is a good way to distribute the benefits of platooning (Smit, 2016; Janssen et al., 2015). Note that such a third party may also involve extra costs.
- Several pilot projects are needed to prove the benefits of platooning. The platooning market, shipper and carriers, will be hesitant when the concept of truck platooning is not tested in real life cases (Smit, 2016; Janssen and Verhaart, 2016). Cooperation between government, carriers, shippers and OEMs is needed to set up pilot projects.

3.5. Conclusion

To describe the perspective of truck platooning, the concept is compared with other freight transport innovations. These innovations have similarities with truck platooning based on their degree of automation or their usage of existing infrastructure. Truck platooning is unique in the sense that it involves both automation and uses existing public infrastructure. Based on the analysis in this chapter, research question 3 and 4 can be answered.

What determines whether innovations in freight transport are successful?
A theoretical framework was created to evaluate different freight transport innovations. Based on the framework enablers and barriers of the selected innovations were identified. It can be concluded that the adoption or diffusion of an innovation is dependent on product characteristics, user requirements and external factors. Transport innovations may look promising and feasible at first hand, but their actual adoption is dependent on many uncertain enablers and barriers.

Which market conditions are favorable for the implementation of truck platooning?
Based on the evaluation of the selected transport innovations and personal communication with expects, the enablers and barriers for adoption of truck platooning were found. It can be concluded that the perception of the market towards truck platooning is an important parameter for the adoption. Only little profits are made in the transport sector and therefore a competitive advantage due to truck platooning is a major enabler. Moreover, the governmental support is important, because governmental organizations are able to create or accelerate the essential cooperation between different truck platooning stakeholders. The next chapter will also estimate which freight flows are feasible for truck platooning under different circumstances.

4

Potential flows and modal impacts of truck platooning

Road freight transport data from the Netherlands are used to estimate the potential of truck platooning under different implementation scenarios. The scenarios are based on the found consequences of truck platooning in Chapter 2 and will be elaborated in Section 4.2. A freight transport model is used to estimate the impacts on the modal split in the Netherlands. The basic structure of this chapter is depicted in Figure 4.1.

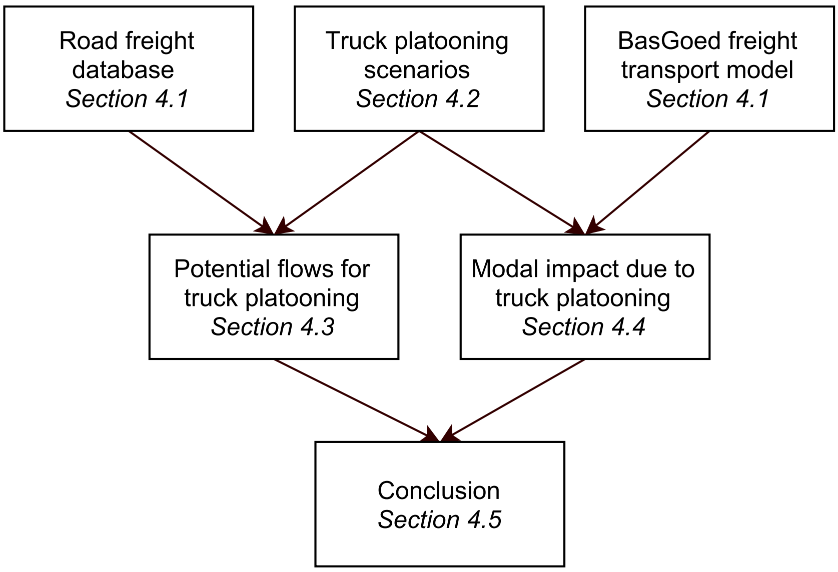


Figure 4.1: Basic structure and used tools.

Many enablers and barriers for the implementation and adoption of truck platooning were found in Chapter 3. The analysis in this chapter evaluates the importance of some of these enablers and barriers. Especially the importance of quantifiable aspects of truck platooning can be evaluated with the used data and method in this chapter. For example, the impact of an increase in road safety can not be estimated with this analysis as it is not known how large the safety increase will be. The importance and effect of the following enablers and barriers can be estimated with the analysis in this chapter:

Enablers	**Barriers**
Realization of fuel consumption savings	No cross-border transport with platoons
Larger truck driver productivity	Low penetration rate at first implementation

4.1. Freight transport data and model

4.1.1. Road freight transport data: Origin-destination flows

As hypothesized in the previous chapters, the concept of truck platooning becomes interesting for large and long distance freight transport flows. To estimate the potential of truck platooning freight transport data are needed. These data should preferably contain information about the origin and destination (OD) of the freight because these should be similar for trucks in a platoon.

Potential truck platooning freight flows are analysed based on the harmonized road freight transport data base for the Netherlands (Basisbestand Goederenwegvervoer). The data base is used as input for several traffic and transport models (CBS, 2016b) and may be used for scientific research by permission of Rijkswaterstaat. The data base consists of trips that are made with Dutch commercial vehicles with a minimum load capacity of 2,000 kilograms in the year 2011. This means that both national and international flows are considered. Though, in reality the number of international trips will be higher as also freight vehicles from other nationalities travel from and into the Netherlands. The data base is based on samples from Statistics Netherlands. The ODs of the data base are distributed over 69 zones, see Figure 4.2. These zones consist of the 40 Dutch COROP-zones and 29 other European zones. A broader description of the data base can be found in Appendix C and the report of CBS (2016b).

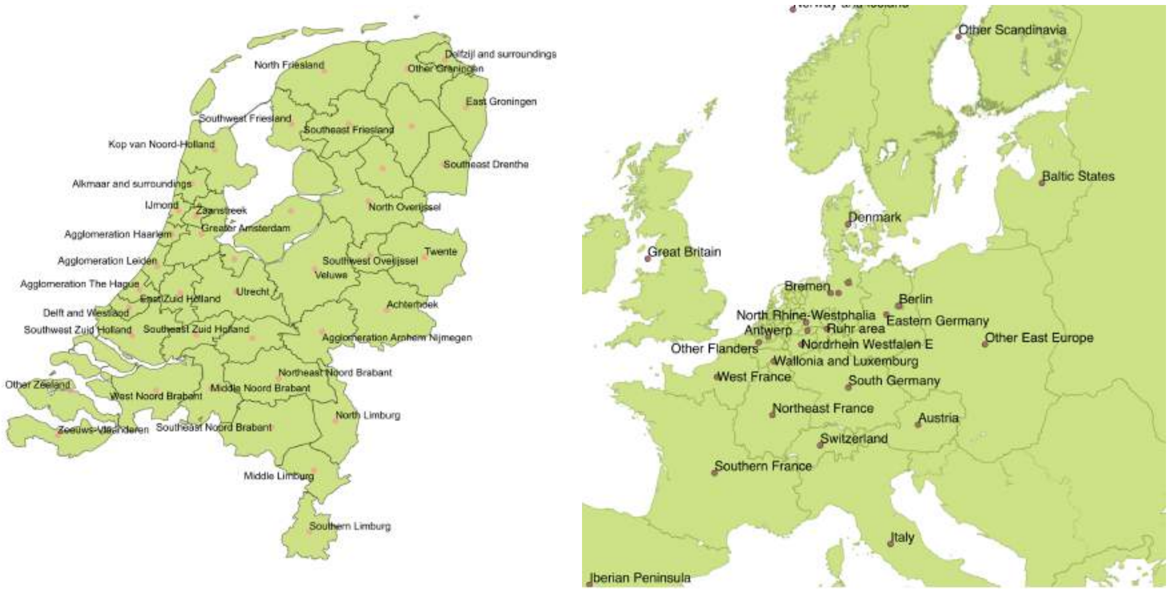


Figure 4.2: 40 COROP zones in the Netherlands and 29 other European zones that are used in the freight transport data base. Source: Adapted from TNO (2016).

4.1.2. Other considered data sources

Also other data sources are considered, the most convenient other sources are described below to give an idea of possible other truck platooning research studies. Open transport data are provided by the NDW (Dutch national data warehouse for traffic information). However, these data are less valuable for this research because only transport intensities are given and no OD information is available (Potgraven and Vroom, 2012). This also holds for the WiM data set (Weigh in Motion) of Rijkswaterstaat which contains detector data of freight vehicles on Dutch highways. To evaluate the potential of coordinated and individual truck platooning shippers were asked for OD flows. These flows are however not publicly available as they contain valuable information about company logistics (Hazelhorst, 2016). The potential of dynamic platooning can be evaluated with OD flows of all freight transport. Two data sets are considered, the used CBS data set and the open data from Eurostat gives origin and destination information of freight on a European level (Eurostat, 2016). This data set is less valuable for this research because the used zones are large and the data is aggregated. Therefore, no clear truck flows can be distinguished. It can be concluded that suitable OD data is hard to find, though the database used in this research gives a proper indication of freight flows in the Netherlands and its neighbouring countries.

4.1.3. Dutch freight transport model

The impacts, especially on modal split, of truck platooning are modelled with the Dutch BasGoed model. This transport model calculates future freight flows for road, rail and inland waterway. The model estimates the distribution and modal split of Dutch freight transport, based on a distribution function and a general cost function respectively. Note that BasGoed does not assign the freight flows to transport networks. Therefore, the output of the model are the freight flows between 69 zones per transport mode.

The BasGoed model uses three types of data: transport data, transport cost data and network information. The transport data base is constructed with data from Statistics Netherlands (CBS) and additional data of other organizations, such as carriers and foreign statistical agencies (De Jong et al., 2011). The data base described in the previous section is one of the inputs of the model. The BasGoed model uses transport cost data to estimate the modal split. A distinction is made between average, variable, fixed, loading and unloading costs, the average load, average load factor and the percentage of loaded trips (TNO, 2016). Finally, network information is used to estimate the distances between the different origins and destinations. These data originate from other Dutch transport models that are also able to assign the different flows. More information about the BasGoed model can be found in Appendix B and the paper of De Jong et al. (2011).

4.2. Truck platooning scenarios

Based on the parameters that influence the potential of truck platooning nine scenarios are constructed. The scenarios are depicted in Figure 4.3 and further explained below.

	Penetration rate; percentage of trucks that is able to platoon		
	10%	50%	100%
Fuel consumption savings due to air drag reduction as only benefit	*Fuel saving (10%)*	*Fuel saving (50%)*	*Fuel saving (100%)*
Longer trip distances can be covered at one day due to driver optimization	*Longer trips (10%)*	*Longer trips (50%)*	*Longer trips (100%)*
High levels of automation result in less driver costs and fuel consumption savings	*Labor costs (10%)*	*Labor costs (50%)*	*Labor costs (100%)*

Figure 4.3: Scenarios for truck platooning based on different penetration rates and levels of automation and cooperation.

The scenarios are based on different truck platoon penetration rates and different implementation phases. The implementation phases are based on the potential implementation of automation and cooperation for trucks described in Section 2.1.3. Penetration rates of 10%, 50% and 100% are chosen to evaluate the truck platooning potential for both beginning stages of platooning as well as the full adoption of the platooning technique. All scenarios assume a platoon length of two trucks. A two trucks platoon is expected to be easier implemented in practice and as explained below, the formation time loss of a two trucks platoon is earlier recovered.

4.2.1. Fuel consumption savings due to air drag reduction as only benefit

Trip distance and truck flow

Truck platooning may result in significant fuel consumption savings. The order of these savings depends on the relative platooning time, the time that a truck platoons compared to the time that a truck does not platoon. The truck flow and the trip distance are used to estimate the fuel savings. This research uses OD flows of general freight transport data, therefore the dynamic formation strategy is used to calculate the benefits of platooning.

Trucks can dynamically form a platoon by adjusting their speed on the highway. The leading truck should reduce its speed until a following truck catches up and both trucks are able to form a platoon. A representation of this formation strategy is given in Figure 4.4.

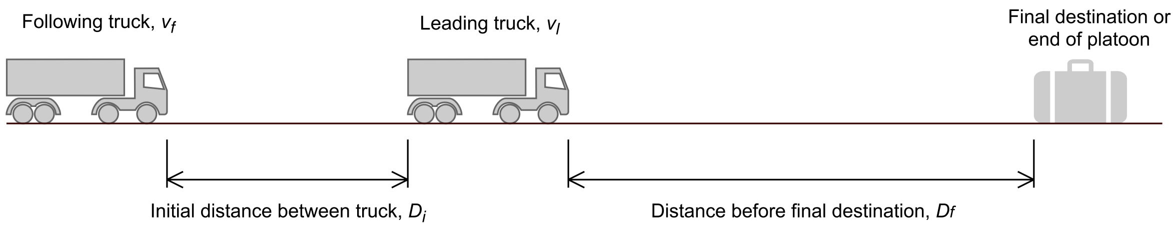


Figure 4.4: Representation of the dynamic formation model setup.
Source: Based on the platooning catch up principle of Liang et al. (2013).

For different frequencies the catch up time and fuel savings can be calculated. For this research a speed difference of 10 km/h is used, i.e. the following truck has a speed of 90 km/h (v_f) and the leading truck has a speed of 80 km/h (v_l) until the following truck catches up. Higher differences in speed may cause unwanted traffic situations due to slow driving trucks and for lower distances the catch up time becomes relatively long. The fuel benefits for this dynamic formation strategy can be calculated with Eq. 4.1. Assumptions and parameters are listed and further explained in Table 4.1.

$$S = \left(D_f - \frac{D_i}{v_l - v_f} \times v_l\right) \times FC \times E \tag{4.1}$$

where,

S	= Savings per kilometer (liter)
D_f	= Trip distance of leading truck (kilometer)
D_i	= Initial distance between trucks based on a specified truck flow (kilometer)
v_f,v_i	= Speed of the following and leading truck respectively (km/h)
FC	= Fuel consumption of a regular truck (liter/kilometer)
E	= Effect of platooning on fuel consumption (%)

Both flow density and trip distance play a major role in the potential benefit of truck platooning. The equation above is used to show the influence of truck flows and trip distances on the platooning benefit, see Figure 4.5. Note that the figure shows the benefits for a two trucks platoon.

As expected, for higher densities and longer distances, the benefits increase rapidly. Note that the calculated savings are based on several assumptions, see Table 4.1. In practice, other traffic participants will play a major role in the formation of platoons. Moreover, congestion or speed regulations may play a role in the order of the platooning benefits. The assumptions were made to show the influence of the platooning distance and the truck flow and to be able to analyse the data for the different scenarios.

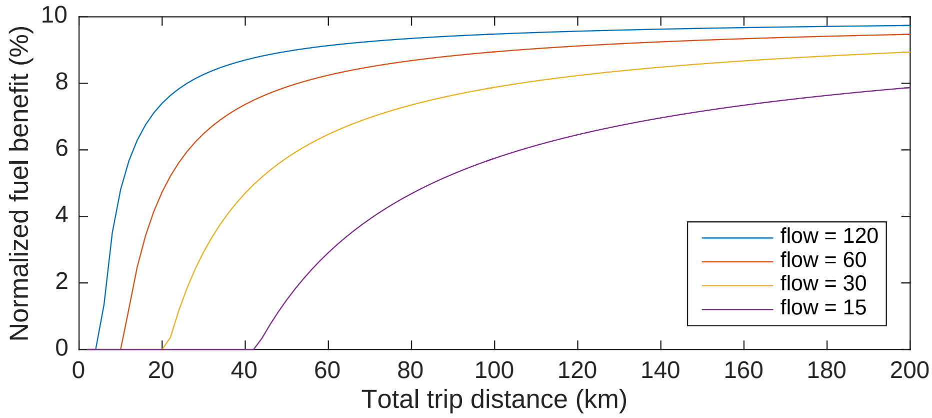


Figure 4.5: Calculated fuel benefits for two trucks platoon dynamically catching up at a highway for different flows (trucks/hour).

Factor (symbol)	Description
Fuel consumption (FC)	The fuel consumption of trucks is assumed to be independent on the speed and the route. It is assumed that a regular truck uses 1 liter of diesel for every 4 kilometer (TNO, 2016).
Fuel savings (E)	As described in Section 2.2.2, there are several ideas and researches about the impact of platooning on truck fuel consumption, however these impacts have not yet been realized. For the calculations in this chapter it is assumed that a two trucks platoon results in 7% overall fuel saving and a three trucks platoon results in 10% fuel saving. These assumptions are mainly based on the SARTRE project (Robinson et al., 2010) and the research of Alam et al. (2015).
Road traffic	It is assumed that the traffic situations are ideal for platooning. This means that once the platoon has formed it is not influenced by any other traffic. Fuel consumption savings may be lower when other road traffic are taken into account. Platooning pilots on public roads will show the actual influence of other road traffic.
Environment	Alam et al. (2015) described that environmental conditions may heavily influence the performance of a platoon. Moreover, the usage of CACC technology may not be allowed under certain weather conditions. These factors are ignored for the calculations in this chapter.
Truck flow (f)	It is assumed that the departure of trucks is equally distributed, this means that the initial spacings between the trucks are all equal.
Fuel price (CF)	The costs of fuel are assumed to be 1 euro per liter.
Value of time (VoT)	The value of time for freight transport is based on the findings of De Jong et al. (2014). The research also distinguishes between different types of freight. For the calculations in this section a general value is used. The value of time is set at 38 euro per transport per hour. A more detailed distinction between different types of freight is given in the section below.
Penetration rate	For the calculations it is assumed that every truck is able to platoon and that there are no restrictions concerning multi-brand platooning. Different penetration rates can be calculated by multiplying the rate by the truck flow.
Equipment costs	Extra expenses for trucks that are equipped with platooning technology are neglected, because as was found in Chapter 2 the costs for platooning equipment are uncertain. Next to that, it is hard to include these equipment costs when truck platooning is only varied against trip distance and truck flow. The next chapter contains a back-of-the-envelop calculation to show the influence of extra equipment costs.

Table 4.1: Assumptions and used values for calculations on the influence of flow density and trip distance.

Time loss and corresponding platoon distance

Drawback of a leading truck that is driving slower or waiting for following trucks is the time loss. The minimum required platooning distance can be calculated when the time loss needs to be compensated by the fuel consumption savings. The time loss can be monetized by using a value of time (VoT) factor. Values of time are used to include non-monetary values into the generalized cost function. The loss of time due to platooning is the time that a leading truck has to wait for the following truck or trucks. This time is directly related to the frequency of trucks. The value of time for freight transport has been calculated by De Jong et al. (2014). The found values of time are based on stated preference surveys amongst carriers and shippers in the Netherlands. The VoT factors depend on transport mode, reliability and type of freight (De Jong et al., 2014, 2004).The following equations are used to calculate the financial benefit. The used input values can be found in Table 4.1.

$$D_{fmin} = \frac{VoT}{f \times S} \quad \text{with} \quad S = FC \times CF \times E \tag{4.2}$$

where,

D_{fmin} = Minimum number of kilometers to reach profit point (kilometer)
VoT = Value of time for freight transport in the Netherlands (euro/second)
S = Savings per kilometer (euro/kilometer)
f = Truck flow (trucks/second)
FC = Fuel consumption of a regular truck (liter/kilometer)
CF = Fuel price (euro/liter)
E = Reduction effect of platooning on fuel consumption (%)

The minimum trip distance of a platoon to compensate for the loss of time is calculated and presented in Table 4.2.

Flow (trucks/hour)	Minimum distance (kilometer)
120	25
84	36
60	51
30	101
15	203

Table 4.2: Minimum trip distance for a platoon consisting of two trucks for different truck flows to compensate for formation time.

Benefits for different platoon lengths

Figure 4.6 shows the monetized benefit for a two and three trucks platoon over the total trip distance. A three trucks platoon has higher fuel consumption benefits, however due to a higher loss of time the minimum required platooning distance is earlier reached for a two trucks platoon. For longer distances a three trucks platoon becomes more beneficial. This trend will increase for platoons with more than three trucks. For the following analysis it is assumed that two trucks platoons are used, because for these formations the formation time loss is compensated for shorter distances.

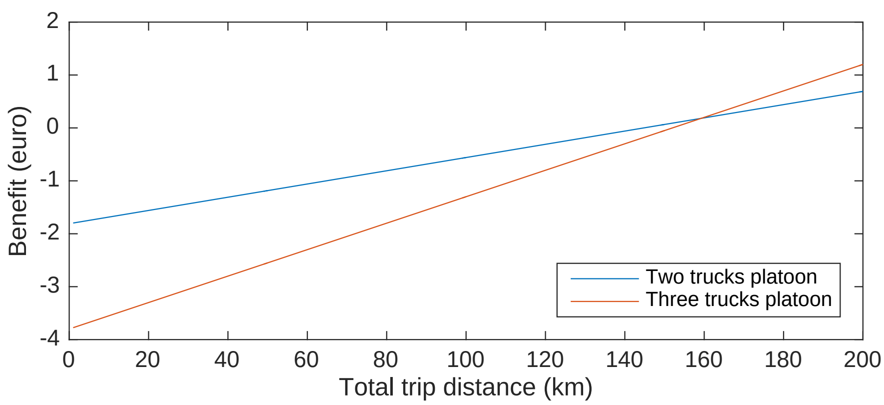


Figure 4.6: Monetized benefit of platooning with two and three trucks, a flow of 60 trucks per hour is used.

4.2.2. Longer trip distances can be covered at one day due to driver optimization

Little or no research about the influence of truck platooning on drivers is conducted. However, it can be assumed that for higher levels of automation (e.g. SAE automation level 3 and 4), driver tasks may become less and their time in the truck may be made more productive. Therefore a situation can be sketched in which a platoon can travel longer distances in which resting time are postponed. Driving time regulations are denoted in the AETR treaty which is part of European legislation (European Union, 2006). The legislation prescribes a maximum driving time of 9 hours per day and an obligatory break of 45 minutes after 4.5 hours of driving. Theoretically, this means that a truck with a single driver can cover 720 kilometer when driving with a constant speed of 80 km/h. The implementation of truck platooning may result in longer driving distances as the productivity of the drivers in the following trucks increases. The time in the following truck or trucks may evolve slower and by overtaking at the right moment a platoon can cover longer distances. To estimate potential impacts and possibilities Tavasszy (2016) assumes that the time in following trucks evolves twice as slow as in the leading truck. Under this assumption, the travel distance of a two trucks platoon can be increased with 25%. This can even increase up to 50% for a platoon consisting of multiple trucks. Note that Tavasszy (2016) assumes a driver productivity increase which is still uncertain in practice. For example, time may evolve slower in following trucks when the drivers are able to rest or sleep on highways (SAE level 4), but this assumption may not be valid when drivers still have tasks (SAE level 2 and 3). More research and pilot projects are needed to determine the effect of automation on the productivity of truck drivers. Figure 4.7 shows a comparison between a regular truck and platooning trucks. In one day, a two trucks platoon is able to cover 900 kilometer instead of 720 kilometer for regular trucks.

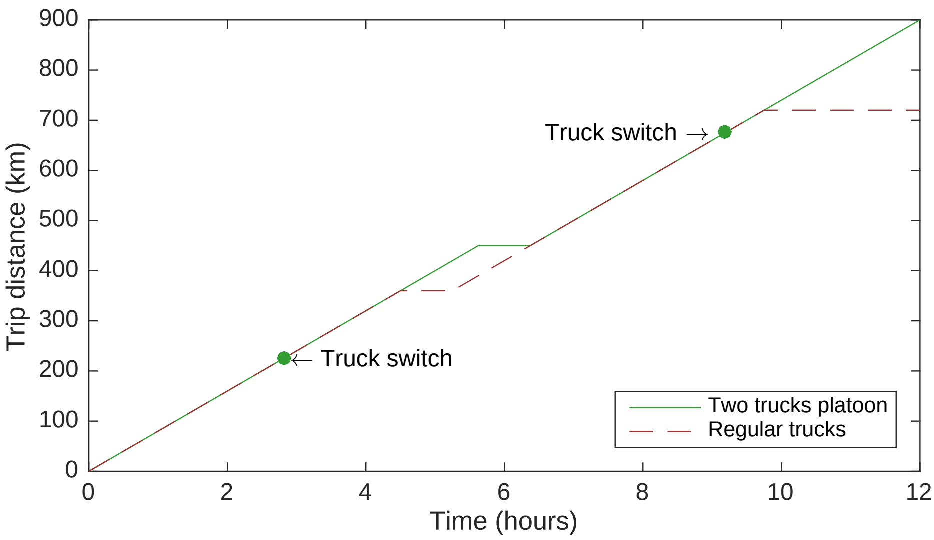


Figure 4.7: Maximum trip distance for a regular truck and a two trucks platoon when driving with an average speed of 80 km/h. Source: Based on the driving time assumption of Tavasszy (2016).

4.2.3. High levels of automation: less driver costs and fuel consumption savings

For higher levels of automation (i.e. SAE level 4), labor costs may decrease as drivers are not needed in every truck. Driver wages is one of the most significant operating cost (Ford Torrey and Murry, 2015) and therefore the potential of truck platooning increases for these higher levels of automation. The minimum required platooning distance to compensate for time loss can be calculated in a similar way as was done for the fuel saving scenario. Minimum required distances are presented in Table 4.3. It is assumed that a driver wages are 25 euro/hour. Also fuel consumption savings are taken into account for the distances presented in the table. Note that origin and destination need to be the same for this scenario, because the following trucks are not able to drive solely. This scenario is constructed because it is able to show the final potential of truck platooning, however it may still take decades before such a scenario will be implemented in practice (Shladover, 2016; ERTRAC, 2015).

Flow (trucks/hour)	Minimum distance (kilometer)
120	1.9
60	3.8
30	7.5
15	15

Table 4.3: Minimum trip distance for a platoon consisting of two trucks for different truck flows to compensate for formation time.

4.3. Potential flows for truck platooning: freight database analysis

The three above described scenarios are evaluated with the data base of the Dutch freight transport (Basisbestand Goederenvervoer) to find the potential number of feasible truck platooning trips. For every scenario, requirements are made based on the benefits and drawbacks of platooning under the conditions of the different scenarios. A certain trip fulfills the requirement when the time losses are compensated by savings due to platooning. So, a trip is feasible for platooning when an OD pair has a specified minimum truck flow and when an OD pair has a specified minimum trip distance. The number of trucks per OD pair can be calculated from the data base. The trip distance between origin and destination is based on the Euclidean distance of the OD-pair, i.e. the straight-line distance between origin and destination. This Euclidean distance is multiplied by a route factor to approximate the actual trip distance. Based on the researches of Robroeks (2016) and De Smith et al. (2007), a route factor of 1.3 is used.

4.3.1. Feasible OD pairs for the different truck platooning scenarios

The OD pairs (69×68) of the used data base are plotted in Figure 4.8 for their truck flow and corrected trip distance. The requirements for the different scenarios are plotted with soid lines. An OD pair fulfills the requirements when it is located above the requirement line. The requirements for the different scenarios are further explained in the sections below. Figure 4.8 only shows requirements for the scenarios with a penetration rate of 100%, requirements for lower penetration rates are presented in Appendix D.

Table 4.4 shows the percentage of trips and the corresponding number of OD pairs that fulfill the requirements for the different scenarios. The percentage of feasible trips is based on the total number of trips. Note that although a limited number of OD pairs seems feasible, the percentage of feasible trips is still relatively high because in general the OD pairs with the highest trucks flows fulfill the requirements. In total 4,692 (69×68) OD pairs were evaluated. Below, the three different scenarios and the potential flows for truck platooning are discussed.

Scenario (penetration)	Feasible trips (%)	Feasible OD pairs
Fuel saving (10%)	0.0	0
Fuel saving (50%)	3.7	5
Fuel saving (100%)	18	42
Longer trips (10%)	0.08	1
Longer trips (50%)	1.0	47
Longer trips (100%)	1.2	79
Labor costs (10%)	27	81
Labor costs (50%)	73	662
Labor costs (100%)	81	930

Table 4.4: Percentage of feasible trips compared to all freight trips and number of feasible ODs.

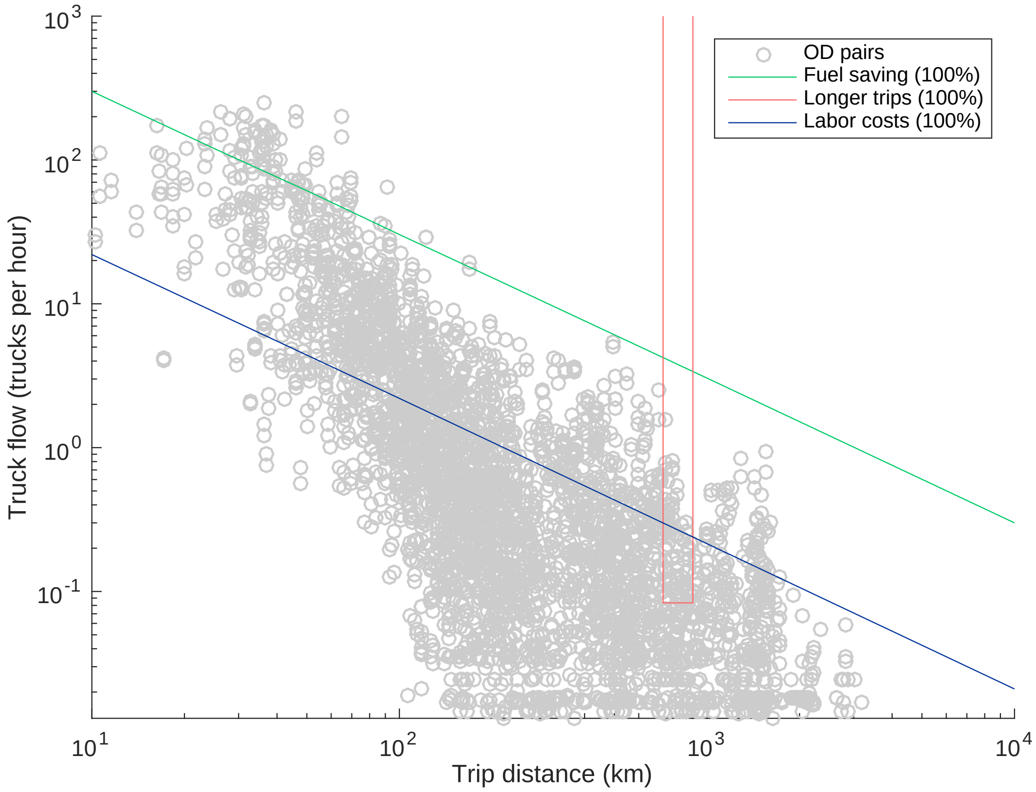


Figure 4.8: Road freight flows of Dutch commercial vehicles for 69 ODs and the requirement for the scenarios.

4.3.2. Potential flows for the circumstances of the fuel saving scenario

As showed in Figure 4.8 only a few origin-destination pairs are eligible for truck platooning under the assumptions of this scenario. Also from Table 4.4 it can be concluded that only a few trips are feasible for truck platooning. Especially for lower penetration rates the number of feasible trips drops. This means that truck platooning is probably not economically feasible when only fuel consumption savings contribute to the benefits of truck platooning, unless high penetration rates are available. However, in the first stages of truck platooning high penetration rates are not likely as the technique can not be implemented at once. So, one can conclude that for the successful implementation of truck platooning other benefits, like an increase in safety or a better road optimization, need to be predominant. Figure 4.9 shows the feasible freight flows for the assumptions of this scenario. In other words, the OD pairs or freight flows that are located above the green line in Figure 4.8 are graphed.

It can be concluded that the feasible flows are mainly relative short routes with a high truck flow. The hinterland transport of the port of Rotterdam seems to take the major part of the feasible freight flows. However, also other flows in the Netherlands are suitable for platooning. Based on interviews and literature, it was concluded that cross-border platooning was essential for the successful implementation of the truck platooning concept. This is contradictory to the findings of this section as this section shows that only national freight flows are feasible for platooning. Thus, based on transport data, the critical development of cross-border truck platooning seems less important for the implementation of truck platooning. Note that this chapter makes the assumption that origin and destination zones need to be the same for truck platooning. Though, it is more likely for longer trips that this assumption is not valid, because trucks will still drive comparable routes without having the same OD. Moreover, not all international freight is included in the database. International platooning trips may become more beneficial when network assignment is taken into account.

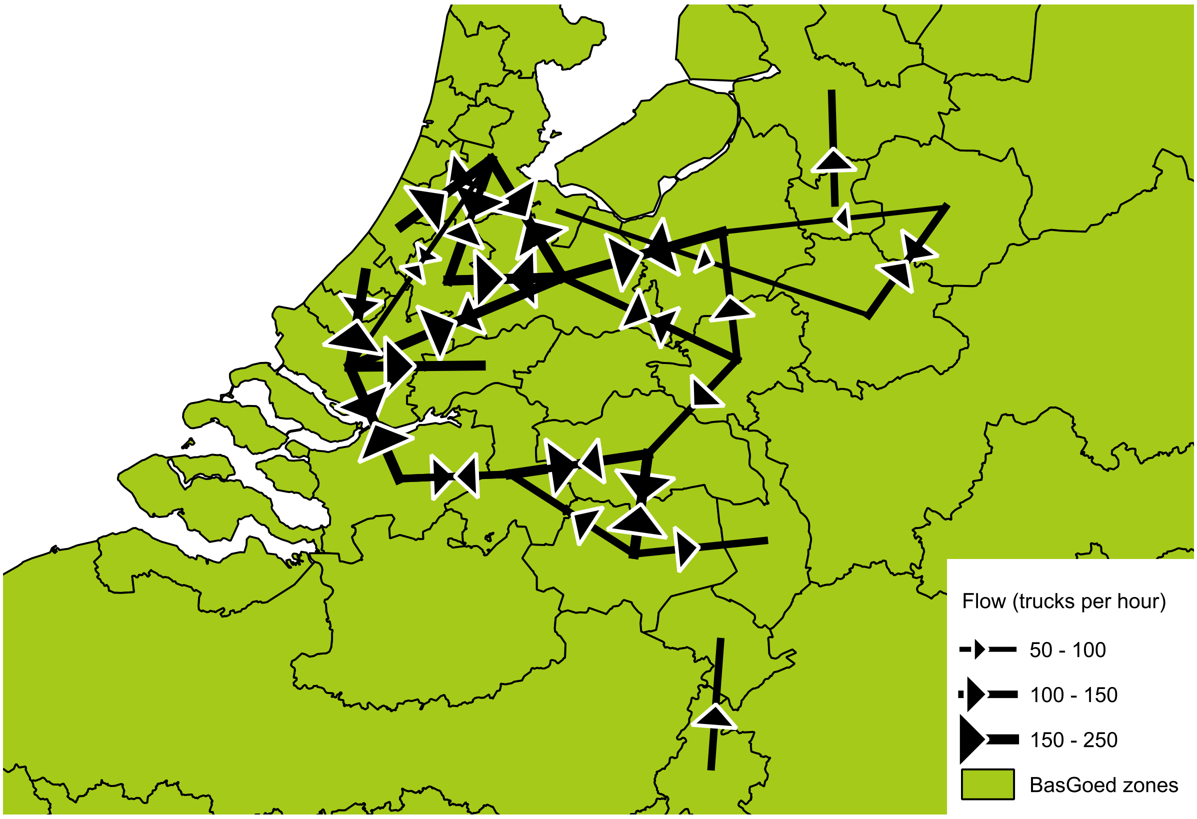


Figure 4.9: Freight flows (plotted between centroids) that fulfill the requirements of the Fuel Saving (100%) scenario.

Fuel saving scenario for individual shippers

Coordinated formation by individual shippers may become beneficial when a shipper transports large volumes over the same route. During the EU Truck Platooning Challenge in April 2016, Ahold announced that they were interested in the truck platooning technology (Wolters, 2016). Ahold and Aholds' main carrier Peter Appel have a lot of trucks on the Dutch roads. For example, during rush hour they approximately drive with seven trucks every five minutes at the Dutch highway A2 in both directions (Wolters, 2016). This is similar to 84 trucks per hour and a minimum required trip distance of 36 kilometer is needed according to Table 4.2. So, one of the largest shippers in the Netherlands needs a minimum trip distance of 36 kilometer under the most beneficial circumstances when only fuel consumption savings result in financial benefits. When the truck frequency becomes lower the benefits for an individual shipper drop and a positive business case with these assumptions is hard to find. Proper logistics planning may result in a more optimal situation for individual shippers. For this example the frequency of trucks is equally distributed. A planning may order the departure of trucks which may result in less time loss. Note that such a planning may also have a negative impacts, like larger batches arriving at distribution centers.

4.3.3. Potential flows for the circumstances of the longer trips scenario

The boundary for this scenario is plotted with a red line in Figure 4.8. It was assumed that at least two trucks per OD per day were needed for feasible trips. Moreover, trip distance requirements are set between 720 and 900 km. This distance range can be covered in one day by a two trucks platoon and not by a single truck. Fuel consumption savings are neglected for this scenario, because with the used data base it is only possible to identify favorable freight flows based on trip distance. Another assumption had to be made for the truck flow requirement (i.e. two trucks per OD per day). Adding fuel savings would make no different because no VoT factor is used and therefore savings or benefits can not compensate for the formation time loss. Fuel savings should be taken into account when the overall financial benefit needs to be calculated.

The requirement line gives a little idea about the potential of this scenario. However, it is more likely that coordinated platoon arrangements will be made to benefit from the longer distance range. One can for example think of an individual carrier that transports flowers between the Netherlands and Spain. When this carrier is able to reach Spain within one day instead of two days it will give him large financial benefits. Such benefits can not be presented or estimated with the used transport data base. The actual potential of this scenario is thus greater than estimated in this research. Moreover, potential flows for the fuel saving scenario and the longer trips scenario differ a lot because the first scenario assumes dynamic formation whereas the circumstances of the longer trips scenario are more suitable for coordinated platoon formation.

4.3.4. Potential flows for the circumstances of the labor costs scenario

The analysis in this chapter shows that there is a large potential for truck platooning under the circumstances of this scenario. More than 80 percent of all trips in the used data base is feasible for platooning when a penetration rate of 100% is used. Truck platooning with the conditions of the labor costs scenario may also be feasible for lower penetration rates. However, in practice the potential of this scenario will be a bit lower because of several assumptions that were used in this research;

- It is assumed that labor costs will be lower because following trucks do not need driver anymore. Though, this can only be true when the origin and destination are exactly the same.
- Larger driver productivity may result in less direct labor costs as drivers may be able to perform other tasks. However, this decrease in labor costs is less than assumed for this scenario.
- Dynamic platoon formation is not possible without drivers in the following trucks.
- Finally, as previously mentioned, it may take several decades before platooning under the circumstances of the labor costs scenario is possible. Other ways of truck platooning implementations are needed before driverless trucks can be adopted.

4.4. Modal impacts of truck platooning

This section estimates the modal impact of truck platooning based on the Dutch transport model BasGoed. First, truck platooning is compared to three other inland modes. Then a potential modal shift due to the implementation of truck platooning is estimated with the transport model. The above defined scenarios are used to estimate the impact of different types of truck platooning. Finally, it is analyzed which type of freight are sensitive for the modal characteristics of truck platooning.

4.4.1. Truck platooning compared to other freight transport modes

A transportation mode is the means by which people or freight are transported. Modes have different characteristics and based on these characteristics a mode or a set of modes can be chosen for a trip. To determine the modal impact of truck platooning it is important to understand the benefits of truck platooning compared to its competitive modes.

One of the important decisions a shipper has to make is choosing the mode or modes that are used to transport goods from origin to destination. Mode choice can be based on various factors, e.g. cost, distance, time, and volume. Road transportation often is an interesting mode due to its speed, its low barriers of entry and its extensive infrastructure. However, road transport also goes along with several downsides, such as congestion and high fuel and operation costs. Some important choice parameters and their relation with different modes are given in Figure 4.10. Truck platooning is depicted as a new transport mode. This section only compares truck platooning with regular road transport, rail transport and inland waterway transport. Air transport is also showed to position truck platooning in a larger perspective. Truck platooning might be competing with air transport, this is however not evaluated in this research.

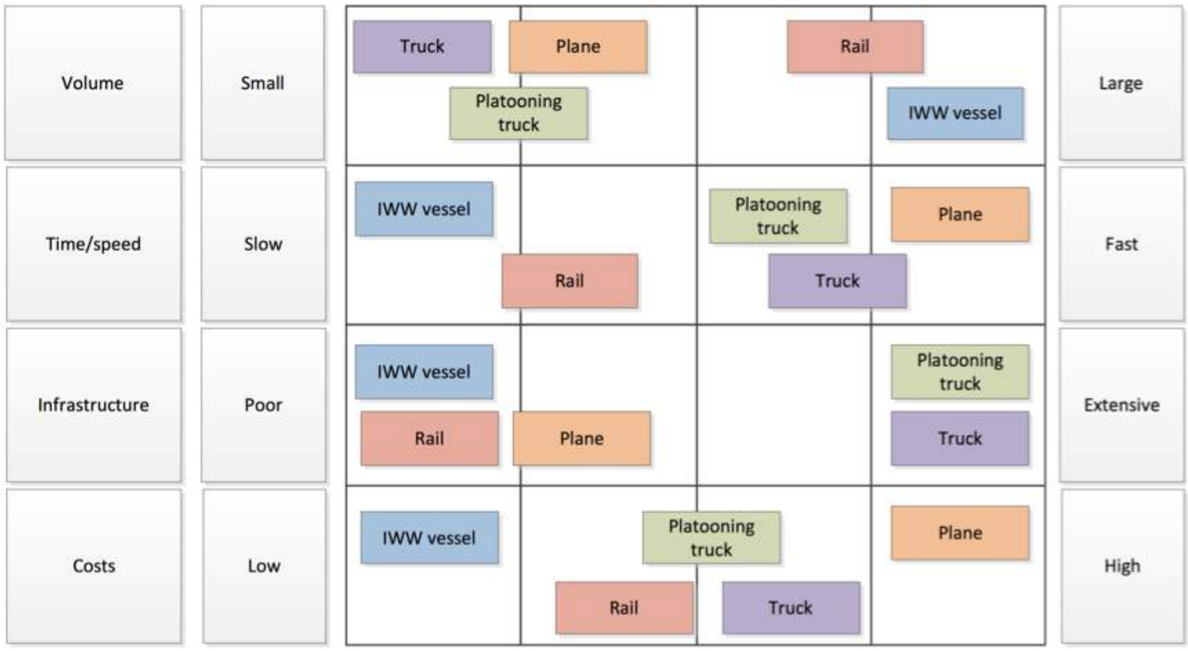


Figure 4.10: Comparison of different modes for different choice parameters.
Source: Based on Rodrigue et al. (2013).

4.4.2. Impacts on freight flows

The Dutch freight transport model BasGoed is used to estimate the potential impact of truck platooning on the modal split and the quantity of road freight transport. The model is suitable for this purpose because it estimates the modal split based on several mode choice parameters. Some of these parameters are also presented in Figure 4.10. Moreover, the model is extensively calibrated and validated because it is also used for policy decisions in the Netherlands (De Jong et al., 2011).

BasGoed uses different forecast scenarios to estimate freight flows in 2020 and 2040. For this research the global economy forecast scenario for 2020 was used. Input values for fuel costs and labor costs are varied to assume the presence of truck platooning. Less fuel or labor costs result in more attractiveness for road transport and may result in a modal shift. No model predictions are presented for the longer trips scenario because it is hard to model the characteristics of truck platooning under these circumstances with the current BasGoed model. Moreover, as was concluded above, only few trips are feasible for this scenario and therefore no significant modal shift is expected.

Table 4.5 shows the impacts in the modal split for the different specified truck platooning scenarios. As expected, larger penetration rates result in a larger modal shift. Moreover, it can be concluded that labor cost savings will significantly contribute to a potential modal shift. The changes are expressed in transport tonnes in Table D.2 in Appendix D. This table also shows that the total quantity of transport freight increases for the truck platooning scenarios.

Scenario (penetration)	Road	Rail	IWW
GE Forecast	65.3	3.69	31.0
Fuel saving (10%)	65.3	3.69	31.0
Fuel saving (50%)	64.6	3.66	30.7
Fuel saving (100%)	66.0	3.63	30.4
Labor costs (10%)	65.8	3.65	30.6
Labor costs (50%)	68.3	3.44	28.3
Labor costs (100%)	72.1	2.97	24.9

Table 4.5: Modal split change due to truck platooning (percentage), based on the quantity of tonnes transported.

Only little changes in fuel costs result in a shift of the modal split; a small shift can be noticed for the fuel scenario with penetration rates of 50% and 100%. This trend is interesting for governments. For example, for societal reasons, the policy of the Dutch government is to shift road transport to rail and inland waterway transport. A potential reverse modal shift may warn governments and they may consider measures against truck platooning. It is also interesting to note that the adoption of truck platooning has a similar impact on both rail transport and inland waterway transport. For some scenarios, the relative share of inland waterway transport decreases even more than the share of rail transport. Apparently the inland waterway flows are a bit more sensitive for truck platooning than the railway flows. The large volumes of inland waterway transport between certain OD pairs are probably the cause of this effect.

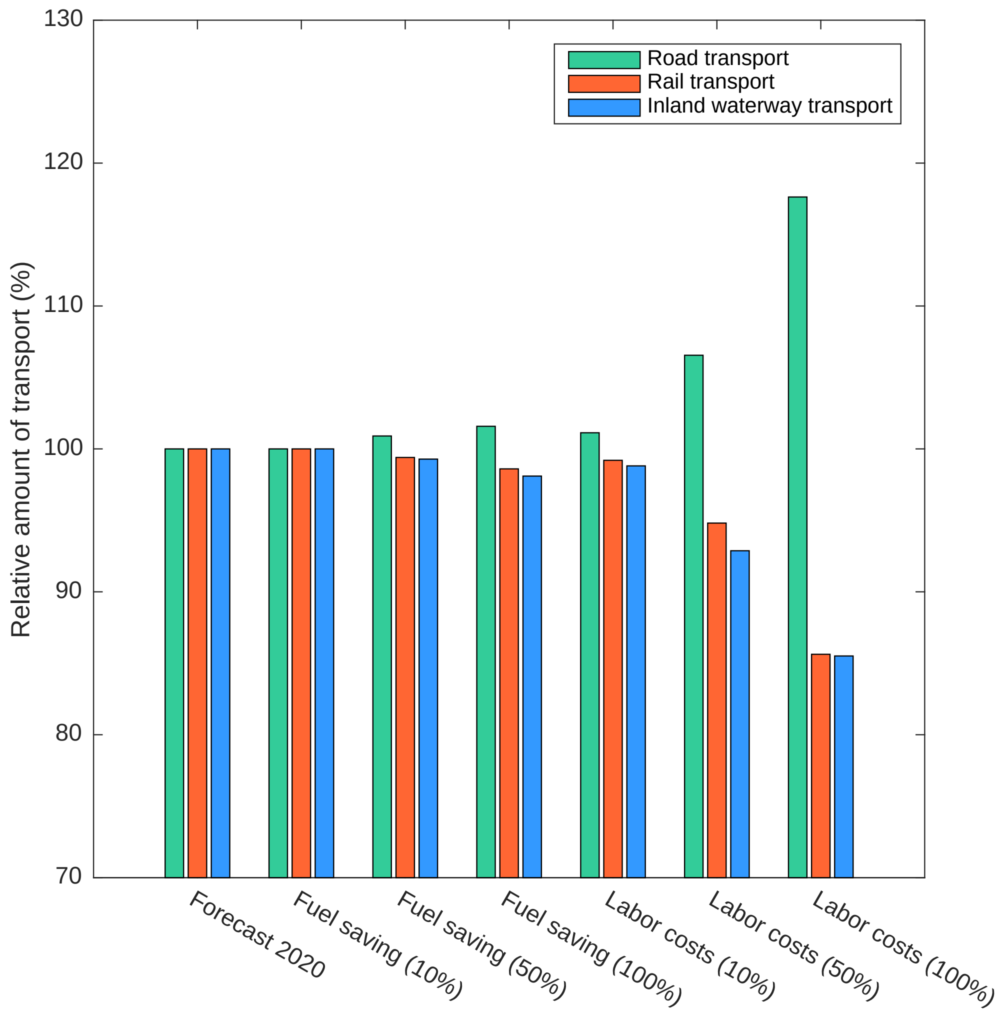


Figure 4.11: Relative mode changes. The truck platooning scenarios are compared with the Forecast 2020 scenario.

The freight flows of the basic Forecast 2020 scenario are compared with the labor costs (100%) scenario to find which OD pairs are mostly affected by the adoption of truck platooning. Figure 4.12 shows all freight flows that experience at least an increase of 10 trucks per hour under the circumstances of this platooning scenario. International freight flows are mostly affected, especially the flows between the port of Rotterdam and the German hinterland become attractive.

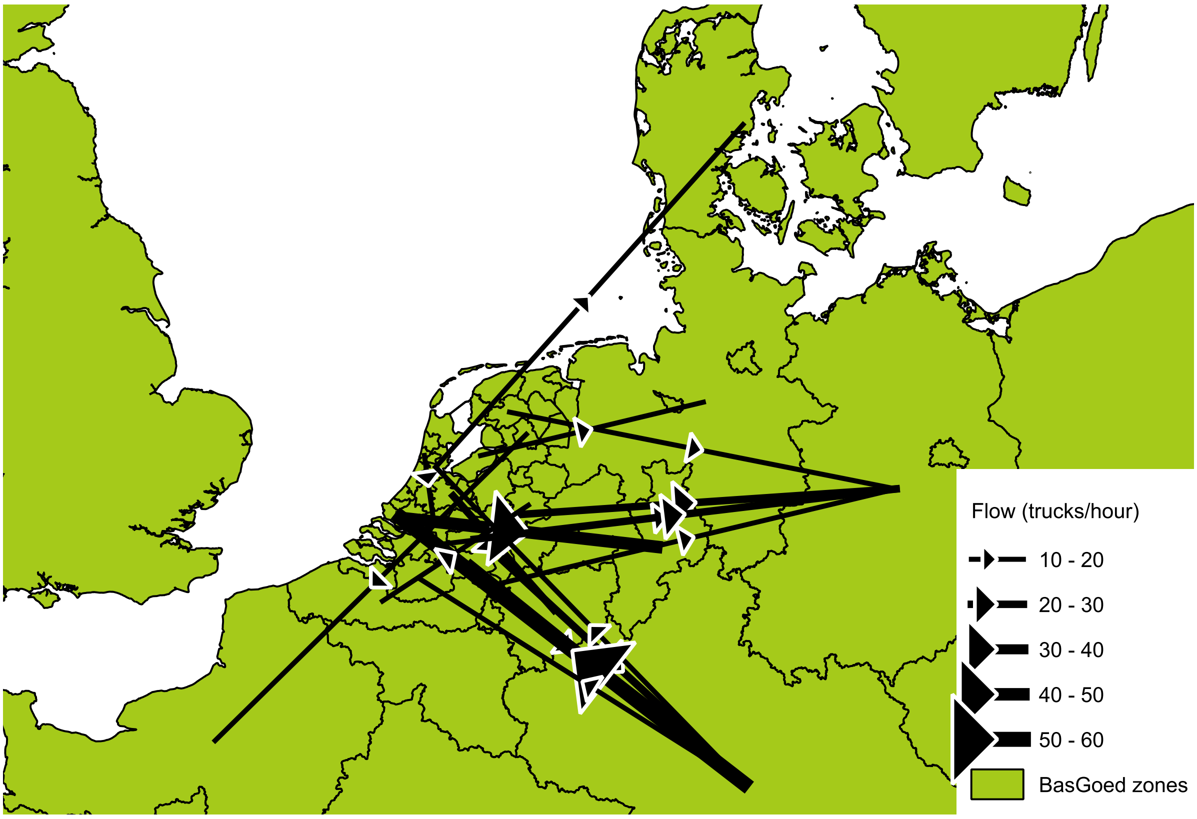


Figure 4.12: Impact of labor costs (100%) scenario. Flows that experience at least an increase of 10 trucks per hour are plotted.

4.4.3. Shift of freight due to implementation of truck platooning

The BasGoed model uses different distribution functions for different kind of commodities. The model is therefore able to distribute different types of freight over the three inland modes. This section discusses the sensitivity of commodities for the implementation of truck platooning. The used distinction of different types of freight in the BasGoed model is based on NSTR-1 classification and presented in Table 4.6.

NSTR-1	Type of good
0	Agricultural products and living animals
1	Other food and fodder
2	Solid mineral fuels
3	Oil and petroleum products
4	Ores, metal waste, iron pyrite
5	Iron, steel, non-ferrous metals (including semi-finished products)
6	Raw minerals and products, building materials
7	Fertilizers
8	Chemical products
9	Vehicles, machinery and other goods

Table 4.6: Classification of goods based on NSTR-1 type.
Source: European Union, 2007.

It can be concluded that the quantity of goods in category NSTR-1 type 9 is overestimated. This was also concluded by (CBS, 2016b). Shipments without a proper commodity classification are classified as 'other goods', thus NSTR-1 type 9. As the level of detail of the input data is not high, the model output should be considered as a rough estimation. However, some trends in commodity shift due to truck platooning can still be noticed.

Figure 4.13 shows the impact of truck platooning on the commodity distribution for the three inland transport modes. The third scenario that assumes savings in fuel and labor costs with a penetration rate of 100% is chosen because this scenario shows the largest commodity shifts. Other truck platooning scenarios show similar trends, but result in commodity shifts with a lower order of magnitude.

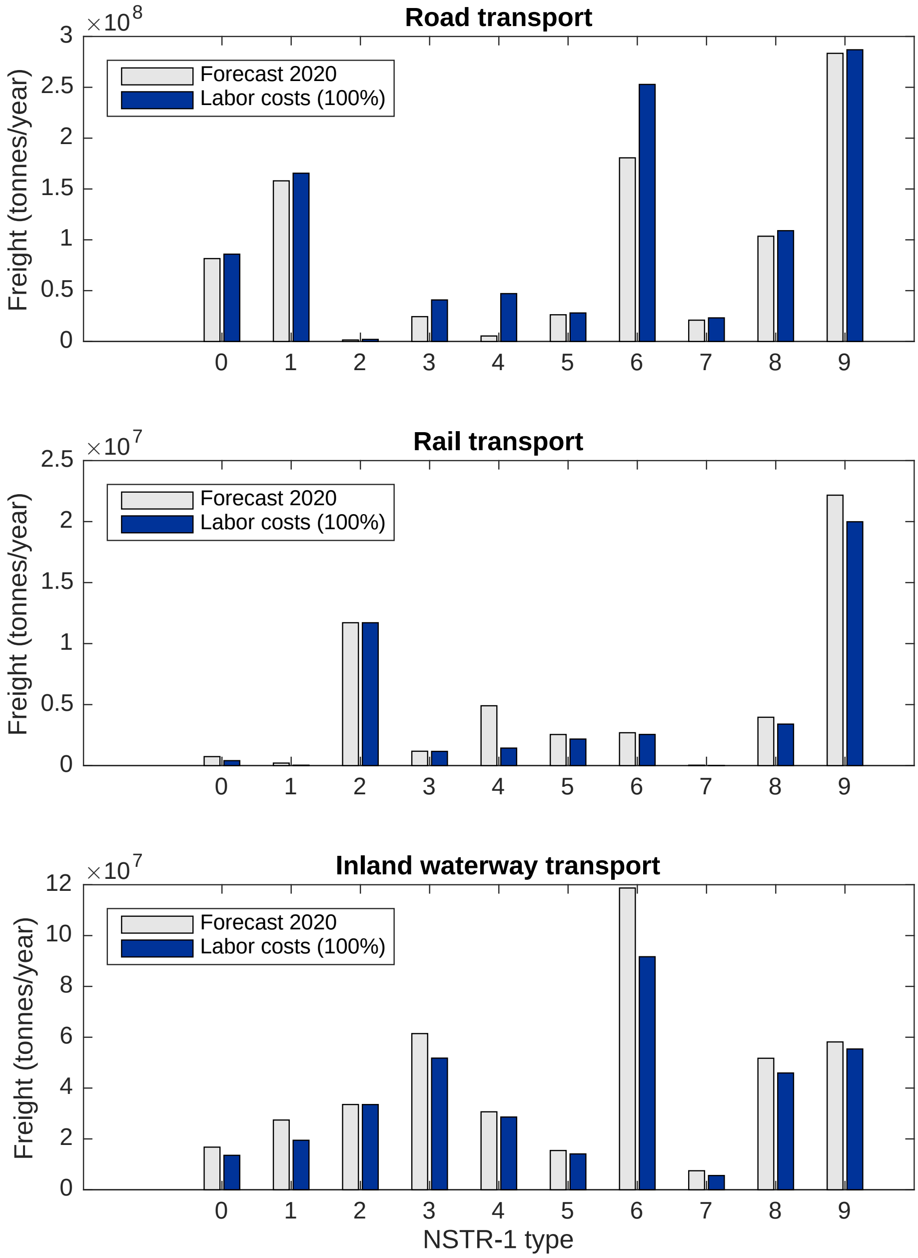


Figure 4.13: Commodity distribution of the basic Forecast 2020 scenario is and platooning labor costs (100%) scenario.

It is interesting to notice that for rail and inland waterway transport different types of freight shift to road transport. Especially ores (NSTR-1 type 4) are sensitive for a shift from rail transport to truck platoons. For inland waterway transport a shift of raw minerals and oil (NSTR-1 type 3 and 6) can be noticed. In practice, it can be expected that such shifts of freight will not take place in this order. The infrastructure and terminal equipment of inland waterway transport is very well developed and travel times are less important for raw minerals and oil.

4.5. Conclusion

This chapter estimated potential platooning flows and modal impact due to the adoption of truck platooning for different scenarios. The truck platooning scenarios are created based on potential development paths. Every scenario encompasses different positive and negative impacts. Only impacts that can be translated into a monetary value were incorporated, i.e. fuel consumption, labor costs, waiting times and driving times. For the different scenarios, potential freight flows for truck platooning were identified based on road transport data of Dutch freight vehicles. In this way, the effect of different earlier identified enablers and barriers was assessed. The major conclusions are:

- When fuel consumption savings are the only benefit of truck platooning, the adoption of the platooning technology does not seem to be feasible. Only a few OD pairs have feasible freight flows for truck platooning under these circumstances. Other enablers are needed for the implementation of platooning.
- For dynamic platoon formation, truck flow seems to be a more important parameter than trip distance. Most feasible flows or OD pairs are selected based on their number of trucks per hour rather than the trip distance between origin and destination. Therefore, most feasible flows have a rather short trip distance. Note that this observation may change when the flows are assigned to a network. In this analysis it is assumed that origin and destination needs to be the same for platooning trucks. This is not necessarily the case when network assignment is taken into account.
- The introduction of truck platooning may result in the possibility to cover longer distances in one day. The transport data showed that this possibility is especially suitable for coordinated formation and individual carriers or shippers. The truck flows for OD pairs that belong to this extended trip distance are rather low.
- Labor cost savings in combination with fuel consumption savings result in large benefits and many feasible OD pairs. Labor cost savings due to platooning can only be expected on the long term. However, its impact on the transport market will probably be large.
- The evaluation of the scenarios showed that the penetration rate of platooning trucks is an important factor for the feasibility of truck platooning. Higher penetration rates directly result in more feasible OD pairs.

Research question 5 and its answer are given below:

How can the expected impact of truck platooning on other transport modes be modelled?
The impact of truck platooning is estimated by comparing the concept of truck platooning with other inland transport modes. A freight transport model was able to model the presence of truck platooning as a transport mode in a future scenario. Therefore, the characteristics and the identified mode choice parameters of regular road freight transport were adjusted to estimate the modal impact.

The following major conclusions were made based on the freight transport model:

- It can be expected that the introduction of truck platooning will result in a change in modal split. Freight will shift from rail and inland waterway transport to road transport.
- Rail and inland waterway transport will be approximately equally affected by the adoption of truck platooning.
- It was found that mainly cross-border trips are sensitive for a modal change. Therefore, it can be concluded that a reversed modal shift may be avoided by not allowing cross-border platooning trips.
- The freight transport model confirmed the hypothesis that low valued goods are more sensitive for a modal change. Rail and inland waterway differ concerning the commodities that shift modality.

5

Integration of results and perspectives of platooning stakeholders

This chapter integrates the different results of this research and relates them to current and future developments of truck platooning. First, the critical developments for the implementation of truck platooning that were found with literature and experts are related to the findings of the freight flow analysis. After that, the importance of different enablers and barriers is discussed. Finally, the perspective of the platooning stakeholders is indicated. The integration in this chapter is used to formulate the final conclusion, which is presented in the next chapter.

5.1. Critical developments for platooning: literature and model

Based on literature and experts, barriers and enablers for the implementation of truck platooning were found. The magnitude or influence of some of these barriers and enablers were estimated with transport data and transport modelling. This section links the two analyses with each other and discusses the similarities and differences of the results of both analyses. The final conclusions and the answer to the research question are given in the next chapter.

Critical developments for the adoption of truck platooning were found and described in Section 3.4. These developments are examined with the results of the transport data and the model:

- It was found that the possibility for cross-border transport with truck platoons is essential for the successful introduction of the platooning concept. Also, during the EU truck platooning challenge a lot of effort was put into cross-border transport. On the other hand, the evaluation of the transport data shows that most feasible freight flows do not involve cross-border transport. So, from the transport data can be concluded that cross-border transport is not as important as was found in the literature study.
- Another essential development that was found with literature and experts opinions is the availability of multibrand truck platooning. The evaluation of the freight transport data also shows the importance of multibrand platooning. Higher penetration rates result in significant more potential or feasible freight flows. High penetration rates can not be achieved when different truck brands can not platoon with each other. Therefore, one can conclude that multibrand platooning is indeed an essential development for the adoption of truck platooning.
- The importance of platooning benefits distribution is hard to evaluate with the available data or model. Though, from the evaluation of the transport data can be concluded that the benefits in the early stages of truck platooning will not be large. Shippers and carriers might be hesitant towards platooning when small benefits are not equally distributed. The following section discusses different stakeholders and their relation towards benefit distribution.

- Finally, the execution of multiple pilot projects was found to be important for the successful introduction of truck platooning. For the estimation of the potential and modal impact of platooning many assumptions had to be made, because the actual benefits and drawbacks of truck platooning are uncertain. For example, the impact of platooning on safety is not yet determined and therefore not taken into account in the analysis in Chapter 4. But also, many uncertainties exist about the fuel consumption savings or the decrease in labor cost due to platooning. So, for a more accurate or reliable analysis of truck platooning, multiple pilot projects are needed.

5.2. Importance of enablers and barriers for used methods

The theoretical innovation framework and five related transport innovations were used to find the enablers and barriers for the implementation and adoption of truck platooning. Based on the transport data and transport model, it was possible to evaluate some of these enablers and barriers. Table 5.1 shows the relative importance of the evaluated enablers and barriers for the different research methods. Different importance levels were found for the four evaluated enablers and barriers. A plus indicates that the enabler is important for the implementation and adoption of truck platooning whereas a zero indicates that is enabler or barrier is found to be less important. Moreover, a minus indicates that a barrier has a large negative impact on the potential implementation of truck platooning. The literature row encompasses the findings of the five related transport innovations. Personal communication is based on the interviews held with different experts (Aarts, 2016; Deelen, 2016; Hazelhorst, 2016; Janssen and Verhaart, 2016; Smit, 2016). Also the interviews held by Verweij (2016) are taken into account. He interviewed different shippers and carriers that are interested in the adoption of truck platooning. Therefore, the current opinion or perspective of the transport market towards truck platooning is also included.

	Enablers		**Barriers**	
	Realization of fuel savings	Larger truck driver productivity	No cross-border transport with platoons	Low penetration rate at first implementation
Literature	++	++	-	-
Experts Personal communication	++	0	-	0
Transport data: flow evaluation	0	++	0	- -
Transport model: modal evaluation	+	++	-	- -

Table 5.1: Relative importance of evaluated enablers and barriers for the use research methods.

Some interesting differences between the different research methods were found. First of all, the literature study and transport market state that fuel consumption savings are important whereas the model shows that only a few flows are feasible for truck platooning when only fuel consumption savings are taken into account. The actual importance of fuel savings might be overestimated by the transport market. Next to that, the transport data and model shows that a high penetration rate is important for the implementation of truck platooning. According to literature and experts this penetration rate is less important. This might have to do with the type of platoon formation. The analyses with the transport data and model assumes dynamic formation, whereas most experts consider coordinated formation for the first implementation stages of truck platooning. As explained before, a high penetration rate is more important for dynamic formation. Also, notice that expects give lesser value to the larger truck driver productivity. They expect that such enablers will only be available on the long term and thus play a minor role in the implementation of truck platooning. Finally, note that only a few enablers and barriers were assessed with the transport data and model. Other enablers and barriers will also have a large impact on the actual implementation of truck platooning. It is however not possible to assess those with the used methods.

5.3. Perspective of stakeholders in relation with research results

The platooning stakeholders and their relation towards the truck platooning concept are described in Section 2.3. This section discusses the influence of this thesis' analyses on the identified stakeholders. The visibility of the truck platooning concept for the different stakeholders is given in Figure 2.5. It is interesting to notice that during this project (i.e. February - August, 2016) the visibility of the concept changed for the different stakeholders. A peak in public interest or technological push was noticed due to the EU truck platooning challenge and the European presidency of the Netherlands. After that, the actual transport market, i.e. shippers and carriers, became interested and routes or corridors for the first pilot projects were proposed. These pilot projects or real life cases should start in 2017 (De Bruijn and Van Beekum, 2016). A reflection on the proposed routes is given in the next section.

Original equipment manufacturers

In this research, less attention is given to the position and perspective of OEMs. It is expected that trucks that are able to platoon cost €10,000-2,000 extra (Janssen et al., 2015). As long as the magnitude of the platooning benefits is unknown carriers will probably not buy more expensive trucks (Smit, 2016). OEMs have the opportunity to accelerate the research into the benefits of truck platooning. They may for example facilitate platooning trucks for future pilot projects. Once these projects prove the feasibility of truck platooning, potential truck buyers will become more interested. Next to that, OEMs have the responsibility to develop a general platooning system. Multibrand truck platooning was found as a major enabler for the adoption of platooning. Thus, OEMs should cooperate to develop multibrand truck platooning and accelerate the adoption of platooning.

Governments and policymakers

The analysis of enablers and barriers of several freight transport innovations showed that governments often play a major role in the adoption of innovations. Though, it is questionable whether an innovation is sustainable when a lot of governmental support is needed for the adoption of the innovation. For truck platooning, governmental support can be justified to a certain extend because the concept may also deliver societal benefits. Moreover, high penetration rates are important for platooning, and therefore governmental support in the first stages of truck platooning may be needed to reach a certain critical penetration rate. Another argument for governmental support was mentioned by Aarts (2016), she stated that the adoption of truck platooning may also give economic benefits to the Netherlands. For example, the automotive sector benefits from truck platooning.

Rijkswaterstaat is part of the Dutch ministry of Infrastructure and Environment and is responsible for the maintenance and expansion of the Dutch road infrastructure network. Currently, Rijkswaterstaat increases its responsibilities and sets a new approach towards truck platooning (Aarts, 2016). As representatives from the Dutch government they try to coordinate and accelerate the developments concerning truck platooning with the EU Truck platooning challenge. A possible new task for Rijkswaterstaat may be the distribution of platooning benefits over different platooning users. As was described before, the presence of an independent stakeholder which distributes platooning benefits results in a major enabler. Rijkswaterstaat may even act as a platooning service provider as mentioned by Janssen et al. (2015). Such a provider forms and coordinates platoons. In this way, different carriers are able to platoon with each other based on the coordinated formation principle. Though, a government that functions as platooning service provider is debatable because a government is often not unbiased and the function can also be fulfilled by other third parties.

Carriers and shippers

The perception of the transport market towards truck platooning is reported by Verweij (2016). Fifteen different carriers or shippers were interviewed and all of them stated that fuel consumption savings are an important enabler to adopt truck platooning. Some of them noticed fuel savings as the only benefit of platooning. Based on current knowledge, overall fuel savings between 2 and 10% were expected. This research showed that for most ODs truck platooning is not feasible when only fuel consumption savings are taken into account. Therefore, there might be some misunderstanding between the actual potential of platooning and the perceived potential. On the other hand, the adoption of truck platooning may also results in other benefits which were not mentioned during the interviews of Verweij (2016).

Potential freight flows for different truck platooning scenarios were identified earlier in this research. It is interesting to notice that feasible flows for the assumption of the fuel saving scenario are comparable with possible truck platooning corridors appointed by the transport market. During a meeting of the EU truck platooning challenge different carriers and shippers discussed about platooning corridors for the first real life cases of truck platooning. The transport market appointed which corridors or highways are most suitable for truck platooning in their perspective. The result of this meeting is depicted in A.2 in Appendix A. It can be concluded that the analysis of the freight transport data base results valuable outcomes, as the transport market depicts comparable flows for truck platooning.

The analysis of the transport data base showed which routes or corridors are feasible for platooning for different platooning scenarios. The analysis did not estimate the individual or overall financial benefits due to platooning. With some key figures the payback time for the extra costs of a platooning trucks can be calculated, when only fuel consumption savings are taken into account. Such a back-of-the-envelope calculation is presented in Table 5.2. It is assumed that a truck will platoon during 50% of its journey. In practice this parameter will be variable and dependent on several factors, such as penetration rate and logistics planning. It is found that the payback time varies between 3.3 and 16.3 year. The variation has to do with the uncertain investment costs for platooning trucks. The average lifetime of trucks in the Netherlands is 7.4 year, which is not necessarily higher than the payback time. So, also this calculation shows that only fuel consumption savings are probably not sufficient to make truck platooning feasible. Carriers may make profit when the extra investment costs are low or when the platooning distance is high.

Parameter	Input value	Source
Fuel savings due to platooning	7%	Robinson et al., 2010
Platooning distance	50%	Assumed
Distance covered by trucks (Netherlands)	70,000 kilometer per year	CBS, 2016a
Fuel consumption	0.25 liter per kilometer	TNO, 2016
Fuel price	1 euro per liter	De Jong et al., 2014
Extra purchase costs	2,000 - 10,000 euro	Janssen et al., 2015
Average lifetime trucks (Netherlands)	7.4 year	CBS, 2016a
Calculated payback time	*3.3 - 16.3 year*	

Table 5.2: Platooning payback time calculation

Finally, it can be concluded that the attention of the transport market towards truck platooning is low due to the many uncertainties (Smit, 2016). As concluded above, pilot projects are important to estimate and assess the actual benefits of platooning.

6

Conclusion, recommendations and reflection

6.1. Conclusion

The implementation and possible adoption of truck platooning as a transport mode is a complex and uncertain process. This study tried to elucidate the complexity with the following research question:

Which enablers and barriers will the concept of truck platooning face and how do these affect the potential implementation of the concept?

To answer this research question an overall perspective is used in which the conclusions of the literature study and the transport data and model are combined. A theoretical innovation framework was used to analyze five freight transport innovations. This analysis was used to identify enablers and barriers for the implementation of truck platooning. When a certain aspect is perceived as positive for the implementation and adoption of truck platooning it is categorized as an enabler, whereas the opposite applies for barriers. The evaluation of road freight transport database and the freight transport model were used to estimate the effect of the enablers and barriers on the implementation. The most important enablers and barriers and their found effect on the implementation of truck platooning are summed up:

Enablers

Use of existing and public infrastructure	The concept of truck platooning combines automation with the usage of existing public infrastructure. This increases the compatibility of the concept. New infrastructure is often expensive and it may not be clear who is responsible for the infrastructure.
Realization of fuel savings	Truck platooning has the potential to significantly save fuel. This also results in less emissions. Though, the order of fuel savings in practice is still uncertain. It was found that truck platooning is probably not feasible when only fuel savings are taken into account.
Larger truck driver productivity	Drivers in following trucks may be in a standby mode at highways or even disappear for high levels of automation. It can be concluded that coordinated platoon formation is needed to benefit from larger trip distances that may be possible due to platooning. Labor cost savings may largely contribute to the adoption of platooning as many flows become feasible for platooning when labor costs drop.
Increase in road safety	An increase in safety may be a major enabler. It is however uncertain if and to what extent platooning will increase road safety. As mentioned above, truck platooning is not feasible for fuel consumption savings solely. An increase in safety may be a crucial enabler for the implementation of truck platooning. More research and pilot projects are needed to assess the actual increase in safety.

Increase in infrastructure capacity	The CACC system may result in a larger road optimization as trucks drive closer to each other and the system may smooth traffic flows. This effect has also not yet been realized in practice.

Barriers

Bundling of goods needed	Driving in platoons results in transporting larger batches. Negative consequences of bundling can be expressed in platoon formation time. Moreover, cooperation between carriers or shippers is needed to create larger batches, this will lead to extra costs.
Platoon formation time	The influence of this barrier was assessed by using a value of time factor. Platooning benefits are needed to compensate for the formation time. From the analysis of the transport data base can be concluded that many freight flows are not feasible for platooning due to this barrier. Moreover, it can be concluded that the volume of the freight flows is more important than the trip length of the freight flows. This also implies that cross-border transport may not be important for the implementation of truck platooning.
Potential reverse modal shift	A potential modal shift from rail and inland waterway transport to road transport may result in stricter regulations towards platooning. A modal shift due to truck platooning was assessed with the transport model. For almost all truck platooning scenarios a reverse modal shift was found. Especially a decrease in labor costs for road transport would lead to a shift. International freight flows are most sensitive for the reverse shift.
Many different stakeholders with conflicting interests	This research showed that many different stakeholders are involved in the implementation of platooning. Moreover, it can be concluded that cooperation between different competing industries and companies is important. Cooperation should lead to multibrand platooning and the possibility to platoon cross-border.
Shippers' cooperation	The analysis of the transport data base and model showed that a high penetration rate is necessary for feasible platooning freight flows. Such a high penetration rate for dynamic platoon formation can only be achieved when shippers work together.
Uncertain consequences of truck platooning make adopters hesitant	The expected and assessed consequences of the implementation of truck platooning were summed up in this report. It was found that all the magnitude or impact of all the consequences are uncertain. This makes the analysis with the transport model harder. Moreover, it creates a barriers as potential users do not know the exact benefits of platooning.
Low penetration rate at first stages of implementation	Truck platooning becomes more beneficial when the penetration rate of platooning trucks is high. This also means that early adopters of the technology do not reap the full benefits of platooning. Therefore a larger entry barrier is created. Once the penetration rate is high, potential users will be less hesitant to enter the platooning market.

Finally, some effects due to the implementation of truck platooning were found with the help of the freight road data base and the transport model. These are summed up below:

- It is expected that the implementation of truck platooning will have the largest effect on truck flows from and to the hinterland of the Port of Rotterdam. The transport data base showed that these dense flows are most suitable for truck platooning. A dynamic formation strategy should be used for these flows.

- The transport model showed a shift in modal split due to the presence of platooning. Especially platooning scenarios with lower labor costs result in a shift. Both rail and inland waterway transport are affected by truck platooning. An increase in road freight transport up to 18% can be expected due to platooning.

- Larger driver productivity may lead to longer trips. The coordinated formation strategy is needed for such trips, as the flow of trucks is small for longer trips. Though, when regulation allows longer distances at one day due to platooning, some international trips become more beneficial for road transport.
- Especially international transport flows are affected by truck platooning. Here a shift from rail and inland waterway transport is more likely.

6.2. Recommendations

This research focused on the perspective of the transport market and the role of governments towards truck platooning. First, recommendations for those two groups are given. After that, recommendations for further research are presented.

Shippers and carriers

The transport sector is relatively latent towards truck platooning. This is related to the fact that platooning trucks are not available yet and the fact that legislation does not yet provide in rules for platooning. However, this research showed that platooning may result in several benefits for the transport sector. Therefore it is advised to participate in the current discussions concerning truck platooning. Regulators need to know which highways or corridors are most suitable for platooning. And governments need to know which boundary conditions make platooning feasible. So, early participation may create more beneficial circumstances for the transport market. Moreover, truck platooning becomes more beneficial when more trucks are able to platoon. It is recommended to start discussions between different shippers and carriers. In this way platooning corridors can be assigned and cooperation can be easier established.

Governments and policymakers

Governmental support can be justified by the possible societal benefits of truck platooning (less emissions, road capacity optimization, increase in road safety). However, these benefits are uncertain and based on this research a large governmental support for truck platooning is questionable. Moreover, from this research can be concluded that the implementation of truck platooning will probably result in a reverse modal shift and a higher road usage. One may argue that financial support is needed because truck platooning needs a certain critical mass or penetration rate to become feasible. Still, it is recommended to evaluate the current policy of governments towards truck platooning. Especially the Dutch government invests in the concept. It is advised to first assess the consequences of truck platooning and create a larger support from the transport sector. This transport innovation becomes durable when the transport sector itself is willing to invest in platooning. Next to that, governments should be aware that they have many tools or measures to influence the implementation of truck platooning. For example, dedicated lanes for automated transport will accelerate the implementation of platooning. Whereas restrictions on cross-border transport will avoid a reverse modal shift and decelerate the implementation.

Further research

During this study some research limitations and less exposed topics were found. These recommendations are written to improve future studies about truck platooning and may serve as input for other studies or further research.

- It is recommended to research the platooning possibilities for individual shippers and carriers. This research focuses on the general feasibility of truck platooning by estimating feasible freight flows for dynamic platoon formation. Truck platooning may also become feasible for individual shippers or carriers when the coordinated formation strategy is used. Note that information about logistics and freight flows of individual shippers are needed to conduct such a research. During this project it was found that these data are hard to get. It might therefore be an opportunity for shippers or logistics service providers to explore the possibilities for truck platooning with coordinated formation.

- This research assessed the importance of trucks flows by analyzing existing freight flows and using a penetration rate. Other ways of assessing this importance may also contribute to the understanding of truck platooning. One may for example determine a certain critical mass which shows the minimum number of platooning trucks in a flow. For certain conditions, i.e. trip length or type of good, such a critical platooning mass can be determined.
- Freight flows were identified based on different zones. It was assumed that the origin and destination of the flows are located in the centroids of the zones. Trips distances were estimated with a route factor. To estimate the actual truck flows on highways the freight flows can be assigned to a road network. This is especially valuable for long trips where different trucks in a platoon do not necessarily need to have the same origin or destination. Moreover, including network assignment will give more accurate results as flows between zones may also chose different routes.
- The BasGoed model distributes the road freight flows over averaged trucks. The presence of truck platooning can be better modelled when the properties of truck platooning can be inserted in the model and when the model is able to distribute goods over different types of truck. VIAgoed is a new model that is able to perform such modelling. The VIAgoed extension will be available by the end of 2016, see also Appendix B.3.
- The relation between truck platoons and other traffic is not discussed in this research. However, this field is still uncertain and several traffic related questions are still unanswered. One may for example look at the optimal behaviour of a platoon near highway on- and off-ramps or whether a platoon should be deformed during roadworks.

6.3. Reflection

Much attention was paid to the scoping of this thesis. Truck platooning is a relatively new concept and currently different researches about this topic are being conducted. Moreover, governments are investing in the concept as it might result in societal benefits. Scoping was important to not conduct similar researches as other institutes and to answer questions that exist in the transport market. The research was conducted at Connekt, an independent network for smart, sustainable and social mobility. The network consists of governments and several companies in the transport sector (shippers, logistics services providers and carriers). Therefore, this research focuses on the perspective of these parties. When should they adopt the platooning technology or is it wise to invest in the innovation? A consequence of this focus is that less attention is given to other important platooning topics or stakeholders, i.e. the platooning or CACC technology and the OEMs.

Three different kinds of research methods were used; literature study, personal communication with experts and modeling. As truck platooning is a relative new concept, only little literature is available. Especially literature about the implementation of truck platooning was hard to find. Therefore, it was chosen to study literature about the implementation of innovations that are related to truck platooning. It was found that these related innovations share a lot of barriers and enablers with truck platooning. However, the actual relation between the selected innovations and truck platooning is hard to estimate and solely based on literature one can not accurately predict whether or when truck platooning will be adopted. The interviews gave an insight into the perspective of the truck platooning stakeholders. Based on the findings of the interviews some critical developments of the implementation of truck platooning were found. No priority was given to more interviews with for example different carriers and shippers because other institutes already conducted several comparable interviews (e.g. Verweij, 2016; Alkim et al., 2016). Data and modeling were used to quantify the findings of the literature study. The database of CBS (2016b) was the most suitable source. Drawbacks of these data are the less accurate distribution of goods over different commodity classes and the lower availability of international freight flows. As the consequences of truck platooning are not yet measured, several assumptions and simplifications had to be made. Still, according to the authors opinion, the quantification of truck platooning in this research is valuable. The assumptions are well described and their possible consequences are indicated. However, it is advised to not use the precise figures of this research but pay attention to the overall trends and findings. In this respect, reference is made to the LHV case and the predictions of Rosenberg and Lieshout (2005). Their research showed that it is hard to predict the modal impact of a freight transport innovation.

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A

Platooning examples in theory and in practice

This Appendix describes road tests and researches that have been conducted in the field of truck platooning.

A.1. Road tests

A few road tests with platooning trucks have been performed. The most important are shortly described.

The SARTRE project (Safe Road Trains for the Environment) was a three year during project that started in 2009 and was funded by the European Commission (Robinson et al., 2010). Platoons were formed with a leading truck including a professional driver and following cars. The following cars were able to drive automatically resulting in less fuel consumption and no need for the drivers attention.

Alam et al. (2015) describes the findings of an truck platooning experiment under varying environmental conditions. It experiment was conducted in Sweden on public roads with platooning tractor-trailer combinations of Scania. The main conclusions of this experiment are that platooning may result in significant fuel savings under different environmental circumstances and that the road grade has a large impact on the actual savings.

DAF and TNO work jointly on the EcoTwin project (DAF Trucks, 2016). In the beginning of 2015 a road test was performed with a platoon of two trucks. Lateral and longitudinal control of the following truck was automated. Many more road tests and experiments have been conducted by research institutes and OEMs. For more details about these tests reference is made to Milanés et al. (2014); Nowakowski et al. (2015); Bergenhem et al. (2012); Wille et al. (2007).

A.2. Implementation cases from literature

Larson et al. (2015) performed a research to find out when it is economically feasible to merge truck in a platoon. They tried to visualize the trade off between savings of fuel in a platoon and extra fuel consumption due to catching up with the platoon. A platoon velocity of 80 km/h and a catch up velocity of 90 km/h were used. Driving with the catch up velocity results in more fuel consumption compared to individually driving with 80 km/h. Depending on the distance between the trucks and the distance before reaching the destination, it can be determined whether a truck should catch up or not. The research showed that significant cost reductions can be obtained when the initial distance between the truck is rather short, i.e. less than 10 kilometer and when the distance to the final destination is rather long, i.e. more than 350 kilometer.

Van De Hoef et al. (2015) studied how fuel-optimal speed profiles for truck platoons can be computed. An algorithm was created that is able to create cluster plans for a larger number of trucks. Different trucks are informed to adapt their speed and platoons are formed due to this adaption. A theoretical case study for a number of trucks and a hypothetical road network showed that significant fuel savings can be achieved.

Janssen et al. (2015) performed three case studies for the implementation of truck platooning at existing companies. First an application for Europe Container Terminals (ECT) was considered. A small share of their transshipped containers have to be transported to the customs x-ray scanner which is located 16 kilometers away from the container stacking area. The road is explicitly suitable for truck platooning, because it is a remote highway that is mainly used for freight transportation. It was found that despite of the short distance some savings can be achieved by implementing truck platooning for this inter port transport. Two other case studies performed by Janssen et al. (2015) showed that large savings can be achieved by implementing truck platooning at logistic companies in the Netherlands. Platoons can be applied on transport by Peter Appel Transport and De Winter Logistics. These companies can combine their own freight flows and form multiple platoons of trucks. To calculate the savings platoons of two trucks were used and fuel savings were assumed to be 10% for both trucks.

A.3. EU Truck platooning challenge

The Netherlands has hold the presidency of the European Union in the first half of 2016. A priority of the Netherlands during its presidency is giving a platform to innovations. One of the focus points was self-driving vehicles. This focus resulted in the declaration of Amsterdam in which 28 transport ministers of European Union member states signed for agreements on the necessary developments for self- driving vehicles (European Union, 2016). Another initiative of the Dutch government during its EU presidency was the EU Truck platooning challenge.

The EU Truck platooning challenge was held by the Dutch Ministry of Infrastructure and Environment, the Directorate General Rijkswaterstaat, the Netherlands Vehicle Authority (RDW) and the Conference of European Directors of Roads (CEDR) (EU Truck Platooning Challenge, 2016). The aim of the project is to create cooperation between different stakeholders concerning truck platooning.

On April 6, 2016 the landing of the EU truck platooning challenge took place. Six truck platoons (two or three trucks each) of different OEMs drove from several European cities to the port of Rotterdam in the Netherlands. The aim of this event was the accelerate the possible implementation of truck platooning. The findings of the landing are described in the booklet of Alkim et al. (2016). A lot of collaboration between different stakeholders was needed to allow the cross border trips of the platoons. The landing showed that platooning is possible in Europe. However, several issues and difficulties regarding legislation, drivers and other traffic users were found. The main conclusion was that more pilot cases are needed to proof the potential of the truck platooning concept.

Figure A.1: Photos taken during the landing of the EU truck platooning challenge, April 6, 2016.
Source: photos taken by the author.

After the landing some other events were organized by the initiators of the EU truck platooning challenge. On April 7, 2016 the first truck platooning conference was held in Amsterdam. During this conference a vision for the implementation of truck platooning was presented. National and European governments promised to participate and contribute to this platooning vision (EU Truck Platooning Challenge, 2016). Finally, it is worth to notice the Real life cases meeting of the challenge (De Bruijn and Van Beekum, 2016). During this meeting, on May 31, 2016, several carriers and shippers discussed together with OEMs and governments which routes should be used for the first pilot projects of truck platooning. The carriers and shippers that attended the meeting were divided in several clusters. Each cluster proposed a certain project corridor, see also Figure A.2. The corridors are further elaborated for real life cases, as for example exemptions of road authorities are needed to platoon with trucks at the selected corridors.

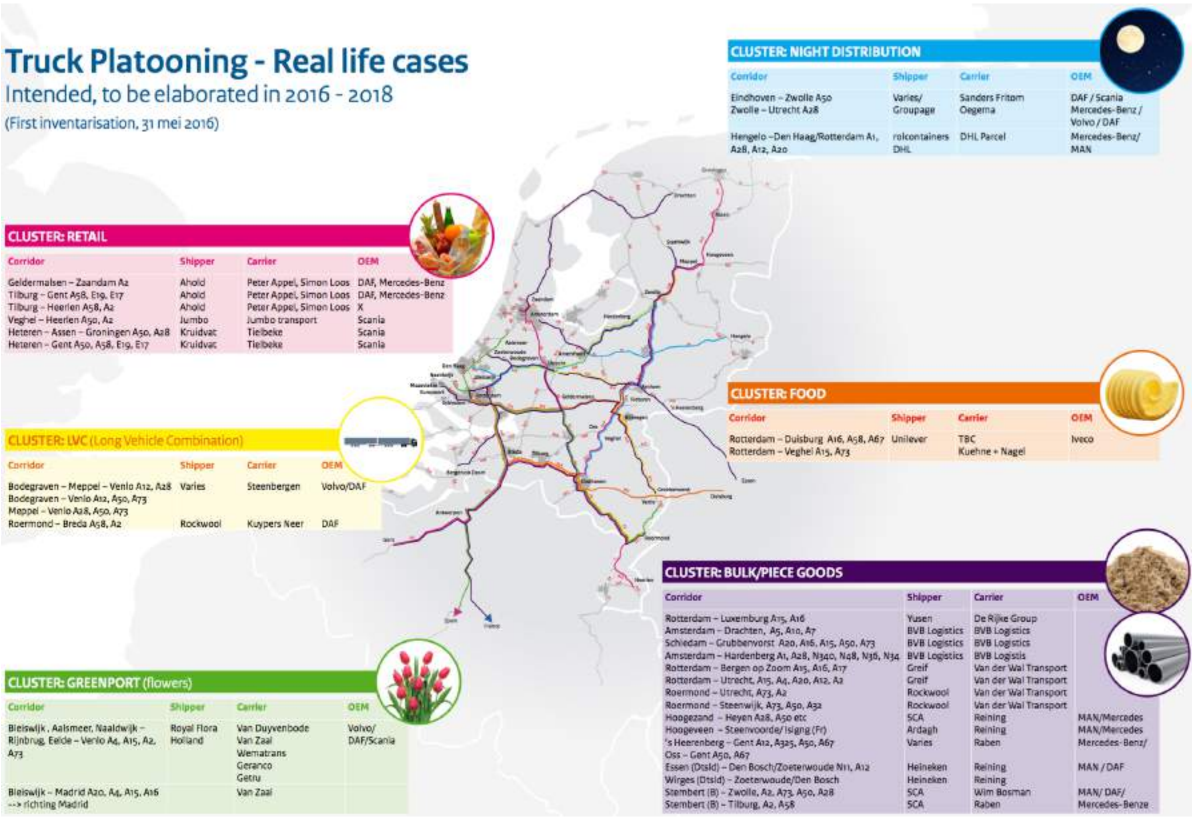

Figure A.2: Truck platooning corridors appointed by different carriers and shippers during the Real life cases meeting.
Source: De Bruijn and Van Beekum, 2016.

B

Dutch freight transport model

B.1. BasGoed model purpose

For this research a Dutch freight transport model called BasGoed is used, this is an abbreviation of the Dutch words ”Basis” and ”Goed”, which mean ”Basic” and Good” in English. The model was constructed in 2010 to fulfill the need of a general freight model in the Netherlands (De Jong et al., 2011). Client of the model is the Dutch Ministry of Infrastructure and Environment. As the model only gives freight flows between different origin and destination, the output of the BasGoed is often used as input for network assignment models. Examples of these assignment models are LMS, BIVAS and ROUTGOED for road, inland waterway and rail transport respectively (Snelder et al., 2012). The BasGoed model is able to estimate future freight flows (i.e. 2020 and 2040) for different scenarios. Four different future scenarios are used; Global economy, Strong Europe, Transatlantic market, Regional communities (Lejour, 2003). Therefore, BasGoed in combination with the different network assignment models can be used for policy and decision making in the Netherlands. BasGoed v3.0 is used in this research (TNO, 2016).

B.2. Model structure

The BasGoed model structure is briefly described based on the reports of De Jong et al. (2011) and TNO (2016). Data sets for the transport modes road, rail and inland waterway are available. For rail and inland waterway transport, origin and destination flow data are available for 69 zones. The 69 zones consist of the 40 COROP-zones of the Netherlands and 29 foreign zones. Moreover, information about the goods is available based on the NSTR-1 categorization. Road transport input data is distracted from the road data base (Basisbestand Goederenvervoer).

Figure B.1 shows the classical four step transportation model and the scope of the BasGoed model. The BasGoed model does not generate the freight because is uses production and consumption per zone as input. Next to that, the model does not assign the model to networks. Separate freight network assignment models are needed to estimate the actual flows on road, rail or inland waterway.

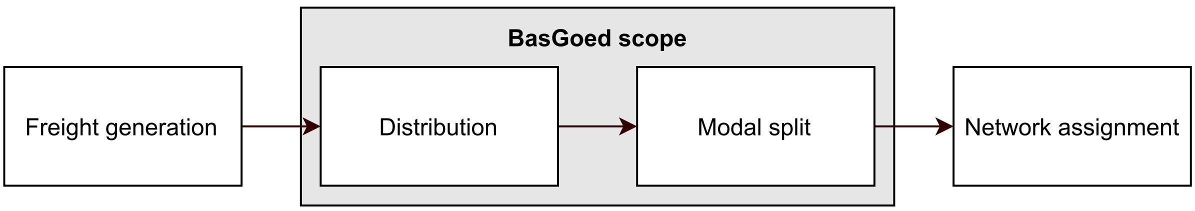

Figure B.1: Representation of the classical four step transportation model and the BasGoed model scope.
Sources: De Jong et al., 2011; Ortúzar and Willumsen, 2011.

B.2.1. Distribution

The distribution part of the BasGoed model produces an OD-matrix for specified forecast year under different scenarios (De Jong et al., 2011). A gravity model is used to calculate the distribution. Logsums are derived with the transport costs per mode, the logsums are transformed to impedances per OD and these impedances are used in the gravity model. The equations below show the general form of the distribution model. For every type of good (NSTR-1) other α and β values were found. Therefore, the model is able to distribute different types of goods to the three available transport modes.

$$r_{ij} = exp(-\alpha \times (c_{ij} + G_{ij})) \times (c_{ij} + G_{ij})^{-\beta} \tag{B.1}$$

$$T_{ij} = p_i \times q_j \times r_{ij} \tag{B.2}$$

where,

r_{ij} = resulting starting value for the impedance between zone i and j (-)
α = parameter of the negative exponential part of the function (-)
c_{ij} = generalized cost or impedance per OD relation (utils)
G_{ij} = cross-boarder impedance per OD relation (utils)
β = parameter of the negative power part of the function (-)
T_{ij} = freight transport from zone i to j (tonnes)
p_i = production parameter of zone i (tonnes)
q_j = attraction parameter of zone j (tonnes)

B.2.2. Modal split

Mode choice is based on a cost function per mode. For rail and inland waterway transport simplified logistical chains are used. Though, basic logistical decisions as terminal transfer costs and shipment size are to some extent included. Eq. B.3 shows the used cost function of BasGoed. Link costs and access/egress costs are included.

$$V_{ijvg} = \beta_{tc} \times (d_{ijv} \times T_v + t_{ijv} \times R_v) + \beta_t \times t_{ijv} + MSC_{iv} + MSC_{jv} + CONT_{ijg} + INT_{ijv} \tag{B.3}$$

where,

V_{ijvg} = costs for the transport one tonne of goods for commodity g between zone i and j by mode v (euro)
β_{tc} = cost parameter for time- and distance costs (-)
β_t = time parameter for the capital costs of the goods during the transit (euro/hour)
d_{ijv} = distance by mode v between zone i and j (kilometer)
t_{ijv} = time by mode v between zone i and j (hour)
T_v = distance unit costs for mode v (euro/kilometer)
R_v = time unit costs for mode v (euro/hour)
MSC_{iv},MSC_{jv} = regional mode specific dummies for origin and destination zone (euro)
$CONT_{ijg}$ = origin-destination and commodity specific containerization degrees (euro)
INT_{ijv} = mode specific border penalty for transport with international origin or destination (euro)

B.2.3. Overall structure of BasGoed model

Figure B.2 shows the overall structure of the BasGoed model. As described above, the input also consists of the freight generation part. Production and consumption per region or zone are estimated with existing other models, i.e. LMS, BIVAS and ROUTGOED. Also the transport times between the different zones are deduced from these transport models.

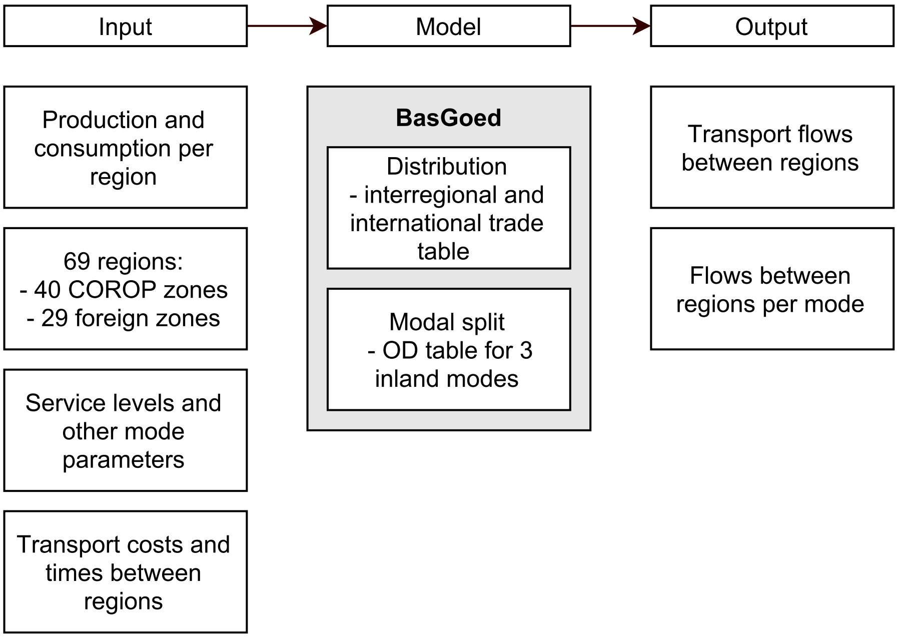

Figure B.2: Description of the BasGoed model including its input and output.
Source: De Jong et al., 2011.

Figure B.3: Different zones and centroids that are used in the BasGoed model. 40 COROP zones are used in the Netherlands and 29 other zones are used for Europe.
Source: Adapted from TNO (2016).

B.3. VIAgoed

The BasGoed model distributes the road freight flows over averaged trucks. The Dutch research institute TNO develops a model called VIAgoed that is able to determine the distribution of freight over different types of trucks (Ligterink et al., 2015). It is expected that the model is available by the end of 2016 and it may significantly contribute to the findings of this research. The VIAgoed model is an extension of the BasGoed model and uses generalized costs functions per vehicle type to estimate the amount of trips per vehicle type. For example, the model is able to calculate the different share of regular trucks and LHVs in the Netherlands. VIAgoed distiguished seven types of freight road vehicles. Truck platooning can be added as extra type of vehicle and in this way the vehicle choice can be estimated more precisely. This research found potential freight flows for platooning and a possible modal shift. The VIAgoed addition could also estimate the actual penetration rate of truck platooning. Four parameters are used to estimate the vehicle distribution; fixed costs, costs per kilometer, costs per weight, costs per volume. These parameters are different for every type of freight vehicle and can also be adjusted to simulate the presence of truck platoons.

C

Analysis of Dutch freight road transport

The data base of CBS (2016b) contains 1,026,467 samples of freight road trips made with Dutch commercial vehicles with a minimum load capacity of 2,000 kilograms. These data are gathered by Statistics Netherlands (CBS). The sample trips are multiplied with a factor to get the final trip estimation. The ODs of the data base are distributed over 69 zones. These zones consist of the 40 Dutch COROP-zones and 29 other European zones. These zones are similar to the zones used in the BasGoed model.

The content of the data base is analyzed with some bar charts below. Figure C.1 shows the vehicle type used for freight transport in the Netherlands. A small share, i.e. less than 1%, is taken by LHVs. Most tonne-kilometers are travelled with a tractor-trailer combination. Such a combination was also used for the landing of the EU truck platooning challenge. Note that the BasGoed model is not able to distinguish the different vehicle types and uses averaged trucks to distribute the goods. The earlier described VIAgoed model extension makes such a distribution possible.

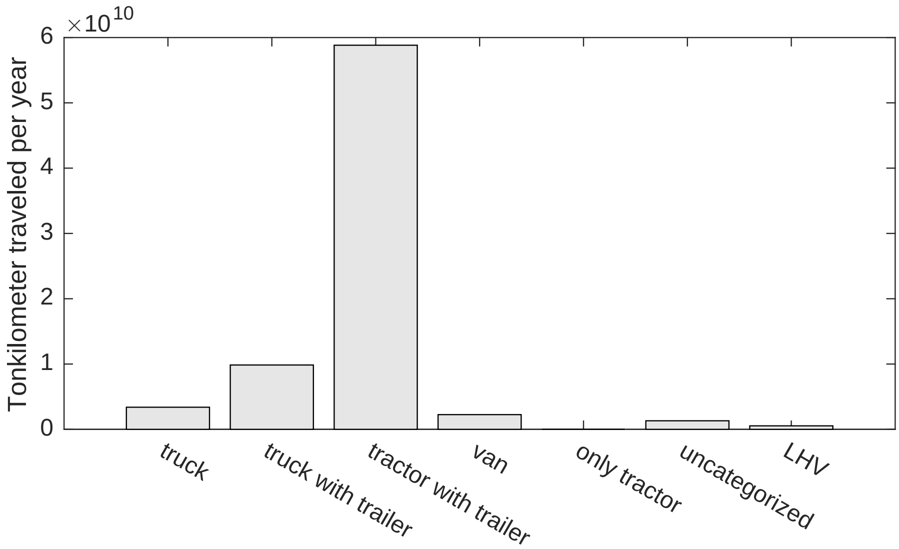

Figure C.1: The amount of tonne-kilometer traveled per year for different vehicle classes.

Figure C.2 shows the distribution of goods over different NSTR-1 types and over different trip distance classes. The number of trips are normalized over the total of each distance class. Most goods belong to NSTR-1 type 9 (other goods). Every trip sample that does not contain information about the transported type of good is classified as other good. This means that the quality of the data base concerning NSTR-1 is not high. However, still some trends can be noticed. NSTR-1 type 0 and 8 (living animals and chemical products) are in general transport over longer trip distances. Next to that, one can conclude that the type of transport good is not much dependent on the trip distance. Figure C.3 shows the dependence between vehicle type and trip distance. As expected, the LHV is more used for longer distances. The most used freight vehicle types (i.e. truck-trailer and tractor-trailer combination) mostly travel shorter distances.

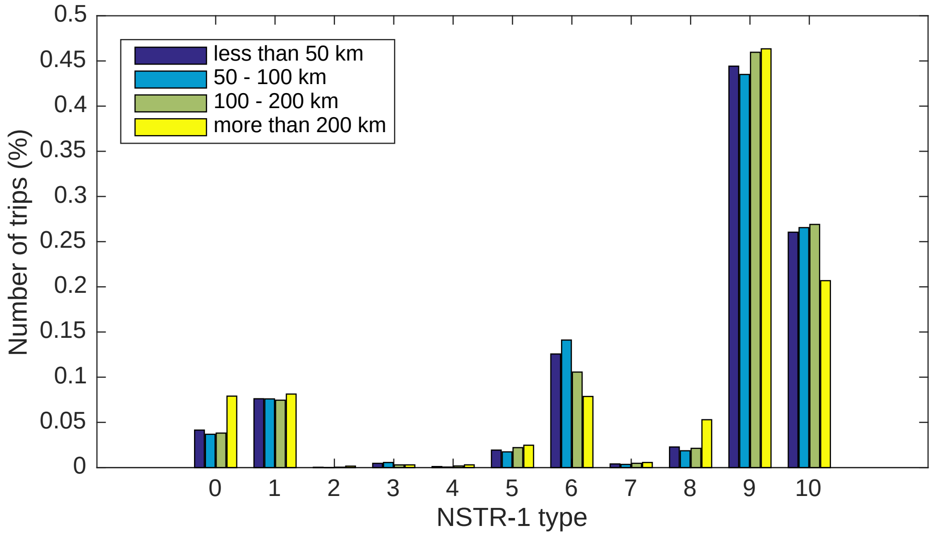

Figure C.2: Relative amount of trips per type of good (NSTR-1) for different trip distances. Class 10 corresponds to empty trips.

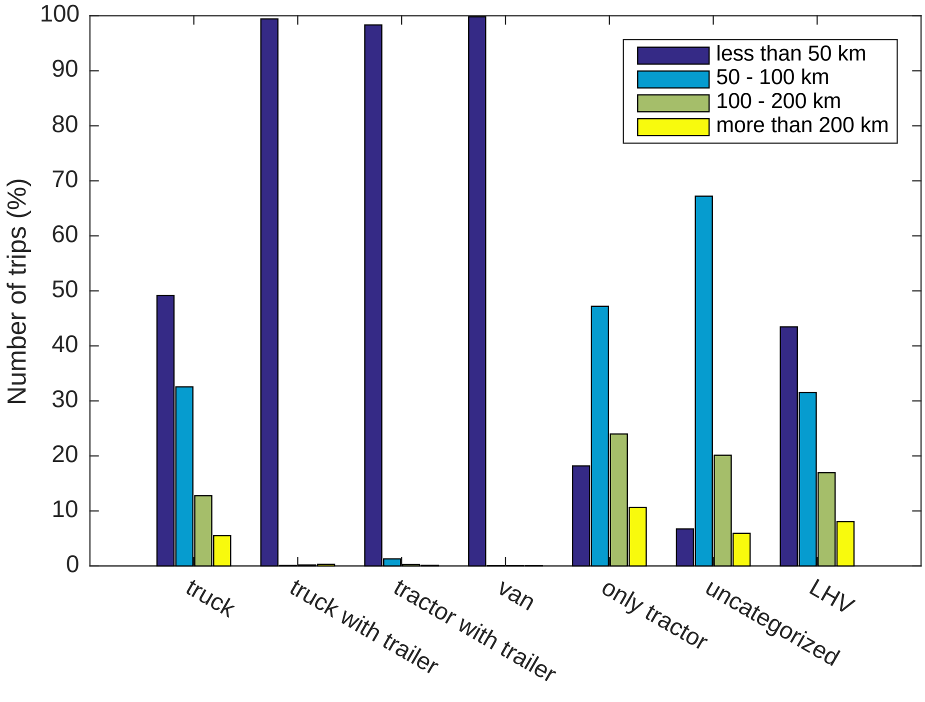

Figure C.3: Relative number of trips in different distance classes for different vehicle types.Quantity of goods transported is normalized for each vehicle type.

D

Scenario input and evaluation

The input factors for the BasGoed model are given in Table D.1. The Base scenario is an estimation of freight flows in 2011. The Forecast scenario gives an estimation of 2020 under a global economy scenario. The different scenarios are based on the Forecast scenario. Different input values are used to simulate the presence of truck platooning for different truck platooning scenarios. Table D.1 shows the freight flows estimated by the BasGoed model. Note that the overall amount of transported freight also varies over the different scenarios.

Input factor	Base	Forecast	Fuel saving			Labor costs		
Penetration rate			10%	50%	100%	10%	50%	100%
Distance costs (euro/km)	0.38	0.38	0.38	0.36	0.34	0.38	0.36	0.34
Time costs (euro/hour)	43.41	43.41	43.41	43.41	43.41	41.24	32.56	21.70
Loading rate (tonne/vehicle)	17.16	17.16	17.16	17.16	17.16	17.16	17.16	17.16

Table D.1: BasGoed input values for different truck platooning scenarios.

Scenario	Road	Rail	IWW	Total
2011 Base	708	36.7	332	1,077
GE Forecast	885	50.1	421	1,357
Fuel saving (10%)	885	50.1	421	1,357
Fuel saving (50%)	893	49.8	418	1,360
Fuel saving (100%)	899	49.4	413	1,363
Labor costs (10%)	895	49.7	416	1,361
Labor costs (50%)	943	47.5	391	1,382
Labor costs (100%)	1,041	42.9	360	1,497

Table D.2: Change in freight transport due to the introduction of truck platooning (transport goods × 1,000,000 ton).

Figure D.1 shows the different requirements of the truck platooning scenarios and the OD pairs of the freight transport data base. Dotted lines represent scenarios with lower penetration rates, e.g. 50% and 10%.

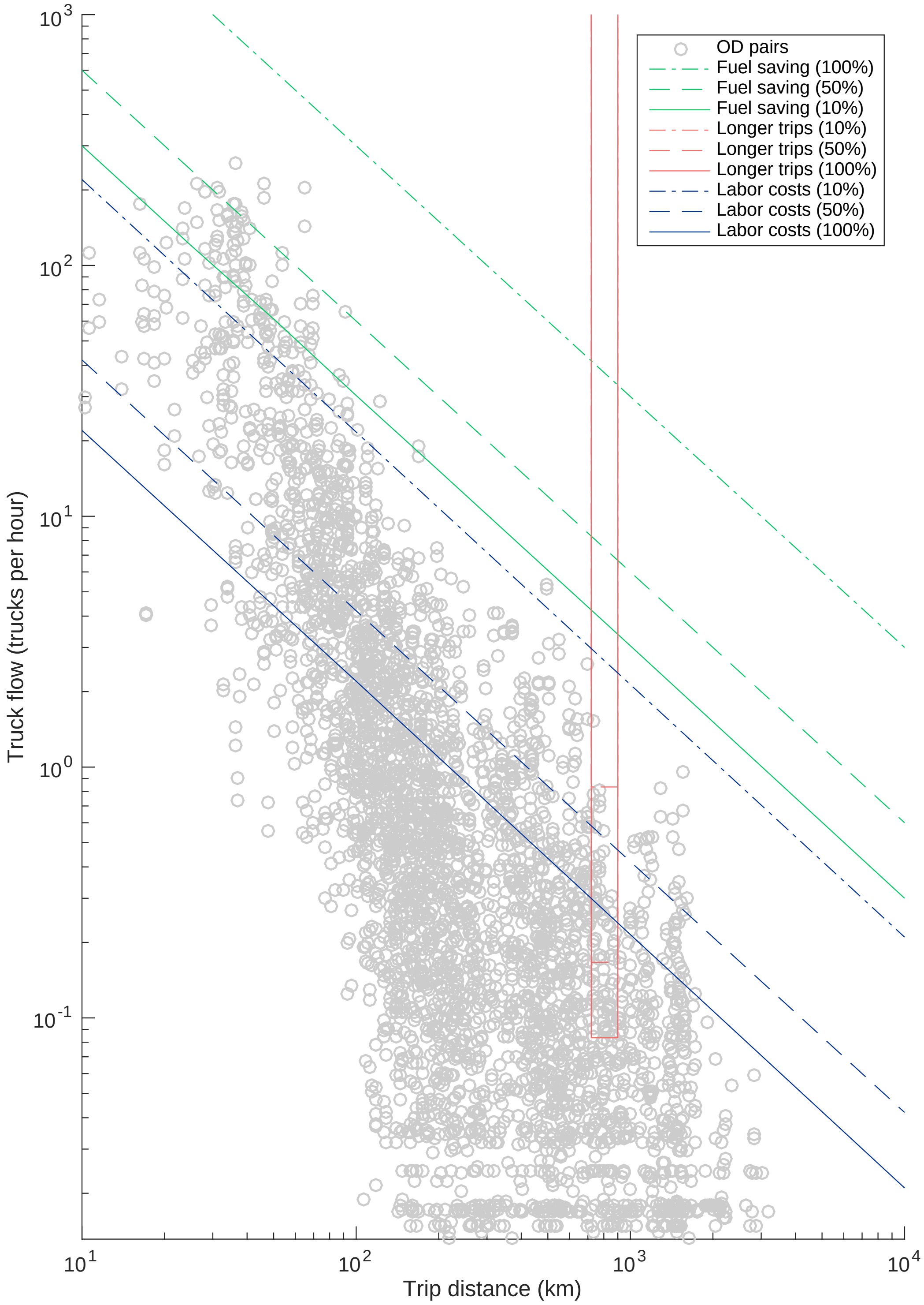

Figure D.1: Freight flows of Dutch commercial vehicles between 69 zones ranked on their flow density and trip distance.