MASTER OF SCIENCE THESIS

TRUCK PLATOONING:

A FRAMEWORK TO OPTIMIZE TRAFFIC MANAGEMENT NEAR THE PORT AREA OF ROTTERDAM

BY

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PREFACE

I thoroughly believe that a clear research connection should be made between the impact of new 'smart' technologies in relation to the built environment. I was always interested in the way infrastructure, movement of people and vehicles have such a large impact on our environment. This research gave me the chance to step slightly out of my comfort zone when it comes to the vehicle technology of truck platooning. Nonetheless, it was very interesting and fun to work on.

I would like to thank first of all my supervisors (Johan, Erik and Marije) of Witteveen+Bos. They helped me to think outside the box and gave me the chance to collect a lot of opinions and information about this research topic. I would also like to thank my supervisors at the university - Gamze, Dujuan and Tom for their support and critical feedback.

With this thesis my 'career' as a student is finally completed. Looking back it was quite a good career with lots of fun memories and meeting new people and hopefully my next career will be even as fun as this one!

Eindhoven, March 2017

Anique Kuijpers

TABLE OF CONTENTS

SUMMARY

Future road transportation must become more safe, secure accessible, environmental friendly and most of all efficient (Pillath, 2016). Truck platooning is a solution to reduce greenhouse gas emission, increase road safety and capacity. However, excessive traffic can lead to the reduction of these benefits (Larsson, Sennton, & Larson, 2015). The interaction between trucks and cars is asymmetric and trucks have a large influence on the behavior of vehicles. With the application of large scale truck platooning it is possible that the benefits cannot be met and only leads to negative effects such as: decrease in traffic safety and no reduction in fuel consumption. Successful implementation of truck platooning on the Dutch infrastructure can only be met if the issues and negative impacts of platooning are predicted and tested to mitigate impacts.

METHODOLOGY

A literature study is conducted to understand the most important aspects of the technology of truck platooning and what the influence is of vehicle behavior on highways. With the literature study, assumptions are made which are used for the experiments. Secondly, a descriptive analysis is executed to analyze traffic data of the A15 corridor. The output of this analysis is used as input for the microscopic model. With microscopic modeling, experiments are executed to analyze the impact of large scale truck platooning on traffic flow, efficiency and safety. Besides that, the results of the experiments are used as a basis where a framework for specific road traffic management strategies can be based on.

RESULTS LITERATURE STUDY

Truck platooning has high attention and is still under development. Truck platooning can be defined as a *cooperative system and the individual trucks are sub-systems* (Bergenhem, Hedin, & Skarin, 2012). Platooning can increase throughput, reduction of fuel consumption and increase traffic safety (Ploeg, 2014). An inter vehicle distance of 6.7 meters (0.3 seconds) with a velocity of 80 km/h is an optimum in relation to fuel consumption. Additionally, the road capacity with this small inter vehicle distance is increased. Trucks on freeways have an impact on the vehicle behavior. Behavior is influenced by road infrastructure, length/size of vehicles, physical and social environment (Ran, Leight, & Chang, 1999; Ferrari, 2009). From the literature study certain assumption can be made:

- Platoon consists of three trucks with an inter vehicle distance of 6.7 meter;
- Platooning increases the throughput, reduction in fuel and safety;
- Behavior of vehicles are influenced by vehicle size, length, fluctuations in velocity and flow;
- Traffic location such as merging and diverging increases traffic conflicts due to the performance of lane changing of vehicles and trucks;
- Road traffic management strategies should react on societal, technological and economic trends;
- Traffic management strategies such as variable speed distributions and left lane driving of trucks could be applied to create dynamic traffic management.

With microscopic modeling vehicle behavior can be analyzed more closely within specific traffic locations. Microscopic modeling describes the fluid process from the dynamics of individual particles (Barcelo, Codina, Casas, Ferrer, & Garcia, 2004). The microscopic model VISSIM is used because with this model the interaction between cars and platoons can be analyzed in detail. The advantages of this simulation tool are:

- Allow studies on heavily utilized motorways to identify system performance;
- Development and analysis of road strategies on motorways;
- Can be applied in multiple scenarios such as mobility studies, intelligent traffic systems;
- It is a behavior based multi-purpose traffic simulator.

However, microscopic modeling with VISSIM has also some disadvantages:

- The model is hard to calibrate and validate;
- Numerous of parameters can be adjusted for the driving behavior, which can increase the inaccuracy of the simulation model

RESULTS DESCRIPTIVE ANALYSIS

Traffic data of the A15 is obtained by SmartPort. The data contains the vehicle category, velocity and intensity of cars and trucks. The data is analyzed in different groups to define traffic scenarios which can be used as input for the microscopic models. The ratio trucks is at its highest during the weekdays and during the day. Based on the descriptive analysis three scenarios are defined that are used as input for the microscopic model.

- Scenario 1: Morning peak hour;
- Scenario 2: Daytime off peak hour;
- Scenario 3: Afternoon peak hour.

Each scenario has is defined by a minimum, mean and maximum intensity of trucks and cars. These intensities are used as an input variable for the experiments in the microscopic model.

RESULTS MICROSCOPIC MODELING

79 experiments are conducted to analyze the impact of large scale truck platooning on the traffic flow, efficiency and safety within the three specific traffic locations. With truck platooning the traffic flow within weaving, merging and diverging areas is increased. However, the traffic efficiency and safety is decreased. This is due to the following factors:

- Performance of lane changing is difficult due to the length and small inter vehicle distance of a platoon;
- Fluctuations in the overall speed within the areas which increases traffic conflicts;
- Merging of platoons is difficult due to other platoons on the road;
- Traffic jams and spillback occur within the traffic locations (weaving, merging and diverging) and up front the traffic locations.

CONCLUSION AND DISCUSSION

Platooning is beneficial for the traffic flow within weaving, merging and diverging areas. Though, the traffic safety and efficiency is decreased by large scale platooning. The results of the experiments are used to create a framework of road traffic management strategies. This framework proposed several road traffic management strategies which could be beneficial when platooning is applied on the Dutch road infrastructure. This framework will give more insight what needs to be done in order the successful implement platooning in the current traffic management near complex traffic locations.

This research contributes to the implementation process of truck platooning in relation to current traffic management. The implementation of truck platooning on the Dutch road infrastructure is a long process. Nonetheless, this research showed that platooning cannot be applied so quickly on the Dutch infrastructure. Further research needs to be done to fully understand the impact of truck platooning in a mixed environment. Mixing types of vehicles on the road requires new policies and strategies to create a safe and sustainable traffic system. Two possible road strategies are variable speed distribution or left lane driving of trucks. The strategies can increase the traffic safety when large scale platooning is applied on the Dutch infrastructure.

SAMENVATTING

Toekomstig wegvervoer moet veiliger, toegankelijker, milieuvriendelijker en vooral efficiënter zijn (Pillath, 2016). Truck platooning is een coöperatief systeem die de doorstroming bevordert, brandstofverbruik verminderd en de verkeersveiligheid kan verhogen. Echter, overmatig verkeer kan leiden tot een vermindering van deze voordelen (Larsson, Sennton, & Larson, 2015). De interactie tussen trucks en auto's is asymmetrisch en vrachtwagens hebben een grote invloed op het gedrag van voertuigen. Met de toepassing van grootschalig truck platooning is het mogelijk dat de voordelen niet kunnen worden behaald en dat dit leidt tot daling van de verkeersveiligheid en de brandstofafname teniet doen. Succesvolle implementatie van truck platooning op de Nederlandse infrastructuur kan alleen worden behaald als de problemen en negatieve gevolgen van grootschalig platooning in kaart worden gebracht.

METHODE

Een literatuurstudie is uitgevoerd om de belangrijkste aspecten van de technologie van truck platooning en het voertuiggedrag op snelwegen in kaart te brengen. Met de literatuurstudie worden aannames gedefinieerd die zijn gebruikt voor de experimenten. Ten tweede, een beschrijvende analyse is uitgevoerd om de verkeersdata van de A15 te analyseren. De uitkomsten van de beschrijvende analyse worden gebruikt als invoergegevens voor het microscopisch analyse model. Met microscopisch modeleren worden er experimenten uitgevoerd om de impact van grootschalig truck platooning te analyseren op verkeersdoorstroming, efficiëntie en veiligheid. Met deze resultaten kan een kader worden ontwikkeld met mogelijke verkeersmanagement strategieën dus kunnen worden toegepast om de implementatie van truck platooning op Nederlandse wegen te bevorderen.

RESULTATEN LITERATUURSTUDIE

Truck platooning staat veelvuldig in de aandacht en is sterk in ontwikkeling. Truck platooning kan worden gedefinieerd als een coöperatief systeem waarbij de individuele vrachtwagens subsystemen zijn (Bergenhem, Hedin, en Skarin, 2012). Platooning kan de doorvoer verhogen, het brandstofverbruik verlagen en de verkeersveiligheid vergroten (Ploeg, 2014). De volgafstand tussen voertuigen van 6.7 meter (0.3 seconden) met een snelheid van 80 km/h is een optimum in relatie tot het brandstof verbruik. Vrachtwagens op de snelweg hebben een impact op het gedrag van overige voertuigen. Gedrag wordt beïnvloed door de weginfrastructuur, lengte/grootte van voertuigen, de fysieke en sociale omgeving (Ran, Leight, & Chang, 1999; Ferrari, 2009). Vanuit de literatuurstudie kunnen bepaalde aannames worden gedefinieerd:

- Een platoon bestaat uit drie voertuigen met een volgafstand van 6.7 meter;
- Platooning verhoogt de doorstroming, vermindering van brandstofverbruik en de veiligheid;
- Gedrag van voertuigen worden beïnvloed door de voertuiggrootte, lengte, schommelingen in snelheid en doorstroming;
- Verkeersknooppunten zoals invoegstroken en weefstroken kunnen een toename creëren van verkeersconflicten door de vele rijstrookverwisselingen;
- Verkeersmanagement strategieën moeten reageren op maatschappelijke, technologische en economische trends;
- Verkeersmanagement strategieën zoals variabele snelheden en vrachtwagens die rijden op de linkerbaan kunnen worden toegepast.

Met microscopisch gedragsmodelering kan het gedrag van voertuigen worden geanalyseerd op specifieke verkeersknooppunten. Microscopisch modeleren kan worden beschreven als een vloeiend dynamisch proces van individuele deeltjes (Barcelo, Codina, Casas, Ferrer, & Garcia, 2004). Het microscopisch model VISSIM wordt gebruikt omdat met dit model de interactie tussen auto's en vrachtwagens in detail kan worden geanalyseerd. De voordelen van deze simulatie methode zijn:

- Het is mogelijk om de systeemprestatie te analyseren voor zwaar gebruikte snelwegen;
- Het ontwikkelen en analyseren van verkeer strategieën op snelwegen;
- Kan worden toegepast in meerdere scenario analyses zoals mobiliteit studies, intelligente verkeerssystemen;
- Het is een op gedrag gebaseerde multifunctionele verkeerssimulator.

Echter, microscopisch modeleren met VISSIM heeft ook een aantal nadelen:

- Het model is moeilijk te kalibreren en te valideren;
- Er is een hoeveelheid aan parameters die aangepast kunnen worden voor het rijgedrag van voertuigen, waardoor onnauwkeurigheden van het simulatiemodel kunnen toenemen.

RESULTATEN BESCHRIJVENDE ANALYSE

Verkeersdata van de A15 corridor is verkregen vanuit SmartPort. De data bevat het voertuigcategorie, snelheden en intensiteiten van vrachtwagens en auto's. De gegevens worden geanalyseerd in verschillende groepen om zo scenario's te definiëren. Deze scenario's kunnen worden gebruikt als input voor het microscopisch model. De verhouding vrachtwagens is het hoogst tijdens werkdagen in de spitsuren. Op basis van de beschrijvende analyse zijn drie scenario's gedefinieerd die worden gebruikt als basis voor het microscopisch model:

- Scenario 1: Ochtendspits;
- Scenario 2: Overdag daluren;
- Scenario 3: Avondspits.

Elk scenario heeft een minimale, gemiddelde en maximale intensiteit vrachtwagens en platoons. Deze intensiteiten worden gebruikt als input voor de experimenten in het microscopisch model.

RESULTATEN MICROSCOPISCH MODELEREN

79 experimenten zijn uitgevoerd om de impact van grootschalig truck platooning te analyseren op de verkeersdoorstroming, efficiëntie en veiligheid in de drie verkeersknooppunten. De verkeersdoorstroming bij invoegstroken, uitvoegstroken en weefstroken is toegenomen door truck platooning. Echter, de verkeersefficiëntie en veiligheid is afgenomen. Dit komt door de volgende factoren:

- Uitvoeren van rijstrookverwisseling is lastiger door de lengte en de kleine volgafstand van platoons;
- Schommelingen in de snelheid bij deze verkeersknooppunten zorgt voor een toename van verkeersconflicten;
- Invoegen van platoons is moeilijker doordat andere platoons op de weg rijden;
- Files ontstaan bij het knooppunt en enkele meters voor het knooppunt.

CONCLUSIE EN DISCUSSIE

Platooning is gunstig voor de doorstroming bij weefstroken, invoegstroken en uitvoegstroken. Echter, de verkeersveiligheid en efficiëntie neemt bij grootschalige platooning af. De resultaten van de experimenten zijn gebruikt om een kader te definiëren welke verkeersmanagement strategieën er kunnen worden toegepast die gunstig kunnen zijn voor de implementatie van platooning op Nederlandse wegen. Dit kader zal meer inzicht geven wat er nog moet worden gedaan om succesvolle implementatie van truck platooning in de huidige verkeersmanagement te bevorderen.

Dit onderzoek draagt bij aan het implementatieproces van truck platooning in relatie tot de huidige verkeersmanagement op Nederlandse wegen. De implementatie van truck platooning op Nederlandse wegen is een lang proces. Dit onderzoek toont aan dat platooning niet snel kan worden toegepast en dat het afhangt van meerdere factoren. Verder onderzoek zal moeten worden gedaan om de volledige impact van grootschalige truck platooning volledig te begrijpen in een omgeving waar meerdere soorten voertuigen zijn. Het mengen van verschillende soorten voertuigen op de infrastructuur vraagt om nieuwe maatregelen en strategieën om een veilige en duurzaam verkeerssysteem te creëren. Twee van de mogelijk strategieën kunnen zijn variabele snelheden toepassen of platoons op de linker baan laten rijden. Dit zorgt voor een verhoging van de verkeersveiligheid als grootschalig platooning is toegepast.

ABSTRACT

Future road transportation can be more safe, environmental friendly, accessible and secure. Truck platooning can optimize the collective behavior to reduce fuel consumption and increase safety and throughput. Mixing platoons with other vehicles can reduce these benefits and can influence lane change performance. This research focuses on the impact of large scale truck platooning on traffic flow, efficiency and safety. It uses a descriptive analysis and microscopic modeling to simulate the impact of large scale truck platooning within critical traffic locations such as weaving, merging and diverging areas. The results showed that large scale truck platooning has an impact on the traffic safety and efficiency within these traffic locations compared to the current situation. Lane change performance is influenced by the small inter vehicle distance and length of a platoon. Vehicles have more fluctuations in acceleration and deceleration which is not beneficial for the overall traffic efficiency. A framework of road traffic management strategies is proposed how the negative effects of large scale platooning could be reduced.

Key words: Truck platooning, Engineering and human factors, Complex traffic locations, VISSIM, Descriptive analysis

ABBREVIATIONS

HDV	Heavy Duty Vehicles
LCA	Lane Change Assist; the systems monitors the areas to the left and right of the car including the blind spot detection
PDC	Park Distance Control; support the driver to maneuver into tight spaced and reduce stress by informing him of the distance
LDW	Lane Departure Warning; helps to prevent accidents caused by unintentionally wandering out of lane
FCW	Front Collision Warning; system is using radar sensors to detect situations where the distance to the vehicle in front is critical and helps to reduce the vehicles stopping distance
ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
PA	Park Assist
V2V	Vehicle-to-Vehicle communication
V2I	Vehicle-to-Infrastructure communication

TERMINOLOGY

Autonomous driving	Vehicles that are fully aware of its surroundings, own location and state and can react up on it
Cooperative driving	Influencing the vehicle behavior by automated actions, to optimize the collective behavior with respect to road throughput, fuel efficiency and safety (Ploeg, 2014)
Truck platooning	Cooperative system of trucks with state-of-the art technologies
String stability	The attention along the string of vehicles of the effect of disturbances, such as initial condition perturbations or unexpected velocity variations of vehicles in the string (Ploeg, 2014)
Lateral control	Steering of the vehicle by lane keeping maneuver and lane-change maneuver
Driving behavior	The movement of vehicles within a network that is subjected to the overall traffic characteristics and behavior of the traffic network and the behavior and characteristics of other vehicles
Merging	Performing lane changes to drive on the main road
Diverging	Performing a lane change to drive of the main road
Weaving	Performing lane change to merge or diverge on/ or off the main road

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION: SMART MOBILITY AND ITS CHALLENGES WITHIN THE URBAN ENVIRONMENT

In the upcoming 50 years the population will increase within cities. Urbanization gives opportunities but also challenges. Cities are establishing strategies on how to achieve a smarter sustainable city. The smart city concepts focusses on various areas with smart mobility as being one of these areas. With intelligent transport management processes the quality of life can be improved (Garau, Masala, & Pinna, 2016). Smart mobility has various themes and one of these themes is truck platooning.

This chapter describes the motivation of the research topic. Section 1.1 gives a brief explanation of smart mobility. Section 1.2 describes the problem definition and goal of this research. The research questions and the related sub-questions are described in section 1.3. To analyze the problem stated in this master thesis a specific research methodology is used. The research design is described in section 1.4. The possible outcomes of the research is described in section 1.5.

1.1 SMART MOBILITY – THE FUTURE OF TRANSPORTATION

The prediction is that urban road traffic will increase in the upcoming years due to urbanization. Transportation is an important element of society and the demand for transportation is strongly connected to economic development. The further development and expansion of cities is becoming a bottleneck due to traffic congestion on road networks (Wei, Dolan, & Litkouhi, 2013). In the last decade the efforts for technological improvements and innovation in the transportation sector are increasing. Urban mobility has a key role to promote sustainable developments in cities by the application of intelligent transport management processes that improve quality of life, develop clear definitions of sustainable transportation and reducing greenhouse gas emissions (Garau, Masala, & Pinna, 2016). Digitalization will change the view on the current management and construction of road transport. Future road transport could be more safe, secure, accessible, environmental friendly and most of all efficient (Pillath, 2016). Electric vehicles, car/truck platooning, automated, cooperative and autonomous vehicles are a few developments that might influence the road management and driving behavior. The prediction is that these new types of vehicles will reduce crashes, pollution, increase fuel efficiency, road capacity etcetera.

1.2 PROBLEM STATEMENT

Autonomous and cooperative driving has a potential to lessen mobility problems and to enhance the capacity and efficiency of the transportation system. Helping or removing the task of driving a vehicle will reduce road accidents because the human error is (partially) taken out. Currently, freight transportation has an extensive road usage and leads to negative side effects such as moving bottlenecks, greenhouse gas emission and congestion (Janssen, Zwijnenberg, Blankers, & Kruijf, 2016) Truck platooning is one solution that can possibly prevent these disadvantages. The prediction is that truck platooning will be applied in the upcoming years and in recent years this type of mobility is extensively tested. It is a new and efficient way in order to distribute goods by road. The interaction between trucks and cars is asymmetric. The ratio trucks on specific Dutch freeways is quite high and has an impact on the overall traffic flow.

The impact of truck platooning on traffic flow and safety on Dutch highways is still unclear. Excessive traffic can reduce the benefits of truck platooning (Larsson, Sennton, & Larson, 2015). Autonomous and cooperative driving at specific network locations is more complex compared to other locations in the network. Complex network locations can be described as traffic intersections, merging, diverging and weaving sections. Currently, autonomous and cooperative driving is being tested on highways with as little as possible bottlenecks and with a low penetration level. Previous researches (Khodayari, Ghaffari, Ameli, & Flahatgar, 2010; Khodayari, Ghaffari, Ameli, & Flahatgar, 2010; Ploeg, 2014; Sugimachi, Fukao, Suzuki, & Kawashima, 2013; European Truck Platooning, 2016) focused on the technology of platooning, the inter vehicle distance and the perception of truck drivers. These researches do not elaborate on the transition phase of mobility where the vehicle composition on the road consists of human driven vehicles, smart vehicles, autonomous/automated vehicles and platoons. The impact on traffic management with a various types of vehicles on the road is still unclear (Jongenotter, 2016).

> "THE TEST CASE WITH TRUCKS NEAR ZWOLLE IS A CLEAR FORM OF COOPERATIVE DRIVING, BUT NOT AUTONOMOUS DRIVING. BUT THE MOMENT THAT HUMAN DRIVEN VEHICLES IS MIXED WITH THESE TYPE OF VEHICLES THEN IT WILL GO TOTALLY WRONG"
> (Heijden, 2016).

Policies and road configuration that enhances the road safety, traffic flow and efficiency are all based on human measurement. These policies and especially how the Dutch road infrastructure is organized can be influenced by a new, 'smarter' type of vehicle such as platoons. In the upcoming years a transition phase will start where smart vehicles and human driven vehicles will share the road. Road adjustments and policies are currently based on the relation between human vehicle and infrastructure (Figure 1). With this trias, sustainable traffic safety can be achieved (Wegman, 2016). With the emergence of new, smarter vehicles the relation between the three components might be shifting in the transition phase. With a higher penetration level of smarter vehicles, such as truck platooning, the relation of infrastructure to the vehicle and human driver can shift. With this shift new possibilities and a new way of thinking can arise.

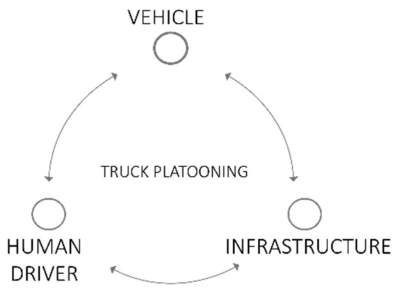


Figure 1: Relations between the different components which have an influence on road policies, adjustments and how the road network is currently organized. This figure is based on various interviews and brainstorm sessions (Hottentot, 2017; Witteveen+Bos, 2016)

To understand the impact of truck platooning on the Dutch infrastructure, further research needs to be done to understand what the impact is of large scale truck platooning on the traffic management. Therefore, it is interesting what the exact impact of large scale truck platooning is on the traffic management of Dutch highways near on- and off ramps and weaving areas. The driving behavior on highways differs in the Netherlands compared to other countries (Marczak, Daamen, & Buisson, 2013). The amount of trucks on the road differs per highway in the Netherlands. One of these highways were the ratio of trucks is higher compared to other highways is the A15 corridor. The A15 corridor is a highway which connects the Maasvlakte II to the inland of the Netherlands.

1.3 RESEARCH QUESTION

The aim of this research is to gain more insight on the impact of truck platooning on the current traffic flow and safety near complex network locations on the A15 corridor near the Port area of Rotterdam. A framework with possible scenarios and recommendations will be developed. The objective of this research is translated into the following research question:

WHAT IS THE IMPACT OF LARGE SCALE TRUCK PLATOONING ON TRAFFIC MANAGEMENT OF THE A15 CORRIDOR?

The sub questions related to the research question are:

1. Which (infrastructure) requirements are needed for truck platooning?
2. How does truck platooning affect driving behavior of other road vehicles?
3. Which road strategies can be applied in order to guarantee traffic flow, traffic efficiency and safety?
4. What is the current state, user behavior and traffic flow management of the A15?
5. Which data is needed and necessary to set up the simulation model?

1.4 RESEARCH DESIGN

The basic research structure to answer the main research question is visualized in Figure 2. First, a literature review is conducted. Numerous of researches are analyzed to understand driving behavior in relation to trucks, environment and exogenous variables. Additionally, extensive research is done about the technology of truck platooning and the impact on the environment. All these aspects and outcomes of various researches are discussed and described in the literature study in chapter 2.

To understand the impact on the road management of the Dutch infrastructure numerous of methodologies can be used. This research will focus on the influence of platooning on the driving behavior of other vehicles. In chapter 3, the methodology that is used in this research is discussed. To represent the characteristics of the A15 corridor in this research a descriptive analysis is carried out. Chapter 4 describes the collection of the traffic data and the descriptive analysis.

Chapter 5 describes the setup and the outcomes of the experiments. Road strategies and dynamic traffic solutions are based on the outcomes of the experiments. This is discussed in chapter 6. Lastly, final conclusions and the scientific relevance is explained in chapter 7.

1.5 EXPECTED RESULTS

The aim of this research is to get more insight on the impact of large scale truck platooning on the driving behavior and the traffic management near complex traffic locations. The prediction is that platooning will enhance traffic management on Dutch highways. Numerous of researches have been carried out to analyze the interaction between cars - trucks and the factors that influence the driving behavior. Based on the literature review it is expected that vehicle behavior is also influenced by the characteristics and size of a platoon. The prediction is that platooning will have an impact on the vehicle behavior and traffic safety near complex traffic locations.

The scope of this research is to gain more insight what the impact of truck platooning is on the Dutch road management. With this research the application of large scale platooning on the Dutch road management becomes more applicable.

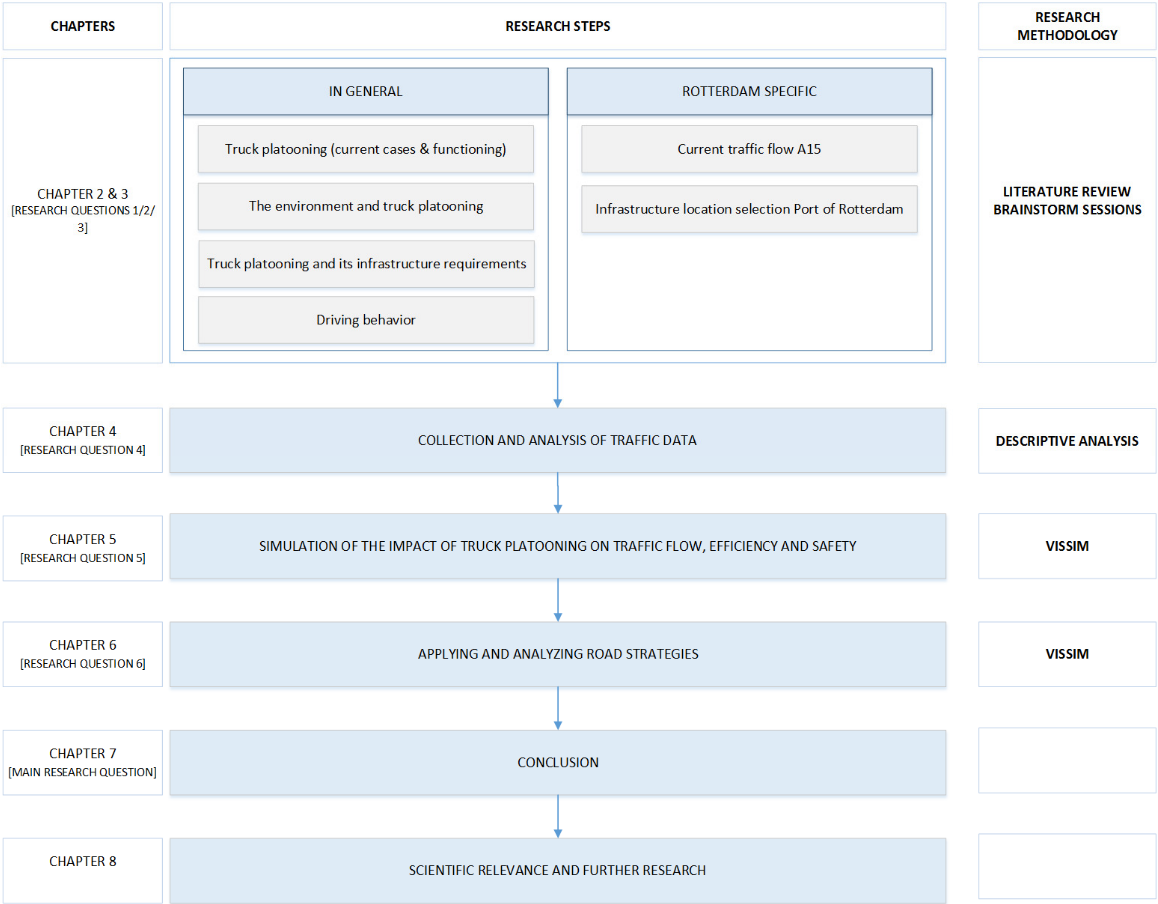


Figure 2: Research methodology

CHAPTER 2

SCIENTIFIC LITERATURE STUDY: THE IMPACT OF TRUCK PLATOONING AND DRIVING BEHAVIOR ON DUTCH HIGHWAYS

ABSTRACT - With new mobility technologies, new problems might arise. One of these relatively new mobility concepts is truck platooning. The developments concerning this type of mobility are currently taken place and new challenges arise. Economical, technological and driving behavioral aspects can influence the implementation process of truck platooning in the infrastructure network. The technology is in high development and short inter vehicle distances of 6.7 meters can be applied. However, the driving behavior of other road users is influenced by the visibility and size of other road users and this can have an impact on the gap acceptance. In order to keep the same level of safety on Dutch road certain road strategies can be applied. Dedicated lanes, HDVs on the left lane and slower vehicles on the right lane are a few examples which can be applied. Numerous of researches are already executed to understand truck platooning. However, the impact on the traffic efficiency, safety and flow on the infrastructure is still not clear and completely analyzed.

Key words: Cooperative driving, Truck platooning, Road traffic management strategies, Human & Engineering factors

2.1 INTRODUCTION

Truck platooning will be the future of transportation and a relatively new concept in the transportation sector. Truck platoons have certain benefits for various stakeholders, the environment and can increase the economy of scale. The implementation of truck platooning in the current urban environment is a complex task. Numerous of factors have an influence on the implementation: technological requirements, legal issues, user acceptance, traffic management etcetera. This new type of mobility might affect not only the traffic management but also the safety of other road users and the requirements of the road infrastructure. An Ishikawa diagram is developed to understand the impact of the parameters that are of influence on the implementation process of truck platooning (Figure 3). The Ishikawa diagram gives a visualization of the complex process of implementing truck platooning in the current traffic environment .

Four parameters are of influence on the adjustment of the road infrastructure: Traffic management, user behavior, technology and economy. This scientific literature review will focus on two parameters: user behavior and traffic management. The other two parameters are not taken into account in this research. Nonetheless, a short elaboration is given on these two parameters to understand the current developments of truck platooning in the field of technology and economy.

The scope of this chapter is to provide an overview of the available literature on truck platooning. In section 2.2, the technology of truck platooning and the developments in this field are discussed. Specific topics on the impact of truck platooning on the environment are discussed in section 2.3. These sections will discuss the advantages of truck platooning but also the challenges that still need to be overcome. Section 2.4 addresses the factors which influence driving behavior on highways and near complex traffic locations. Road traffic management strategies are discussed in section 2.5. In section 2.6, an overall conclusion of the literature study is described. Lastly, in section 2.7 there is a short discussion on the limitations and further research that is necessary to completely understand all aspects of truck platooning.

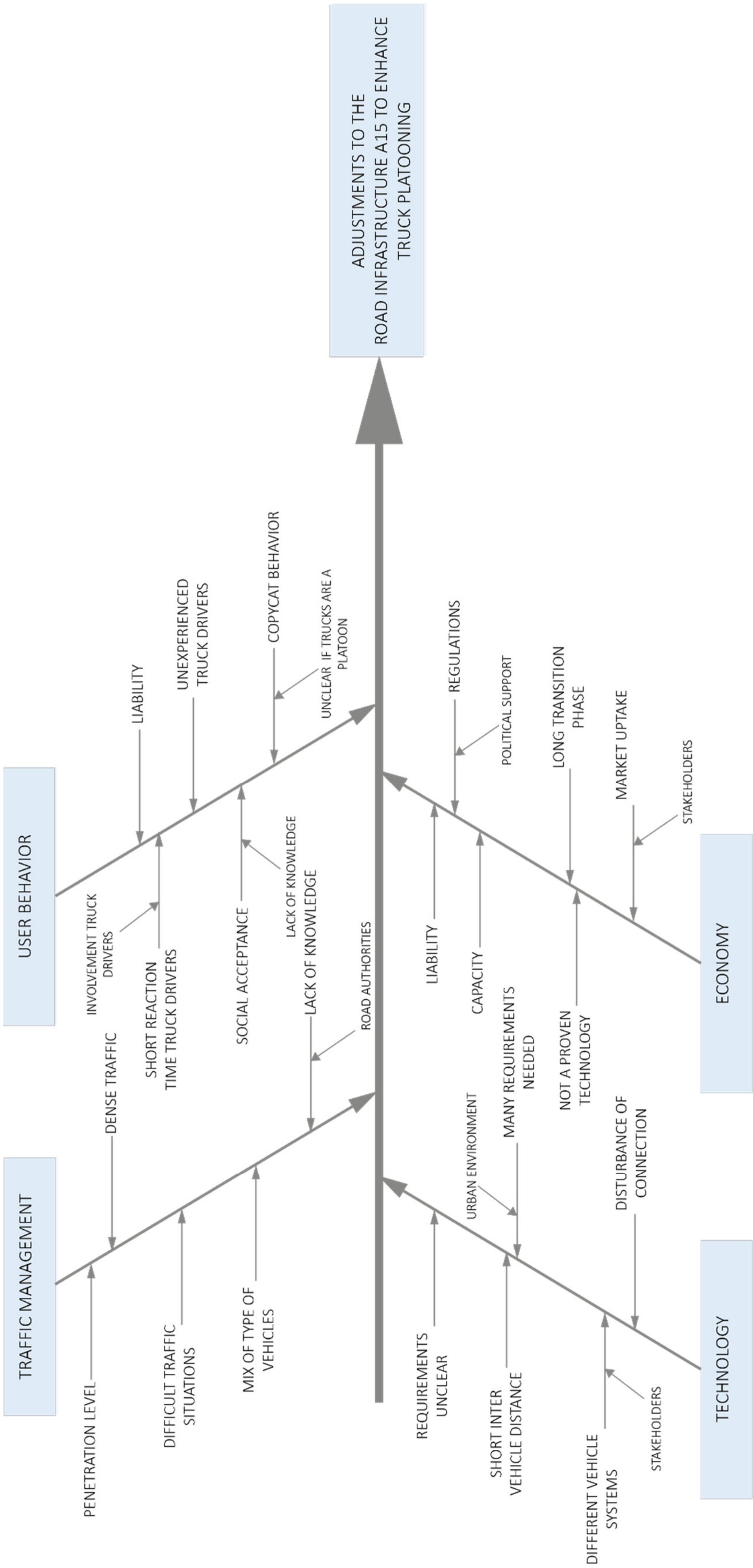


Figure 3: Ishikawa diagram of the difficulties that arise with the implementation of truck platooning (Alkim, Vliet, Aarts, & Eckhardt, 2016; Alam, Besselink, Turri, Martensson, & Johansson, 2015; European Truck Platooning, 2016)

SAE LEVEL	NAME	NARRATIVE DEFINITION	EXECUTION OF STEERING AND ACCELERATION/ DECLARATION	MONITORING OF DRIVING ENVIRONMENT	FALLBACK PERFORMANCE OF DYNAMIC DRIVING TASK	SYSTEM CAPABILITY (DRIVING MODES)
0	NO AUTOMATION	Full time performance by human drivers of all the driving tasks	Human driver	Human driver	Human driver	Not applicable
1	DRIVER ASSISTANCE	Driver assistance is possible of either steering or acceleration/decelaration using information about the driving environment. The human driver is expected to perform all remaining driving tasks	Human driver & system	Human driver	Human driver	Some driving modes
2	PARTIAL AUTOMATION	Driving can be executed by one or more driver assistance systems both steering and acceleration/deceleration using information about the driving environment. The human driver is expected to perform all remaining driving tasks	**System**	Human driver & system	Human driver	Some driving modes
AUTOMATED DRIVING SYSTEM MONITORS THE DRIVING ENVIRONMENT						
3	CONDITIONAL AUTOMATION	The driving mode specific is performed by an automated driving system of all aspects of the driving task. The human driver is however to be expextated that it will respond when there is a request to intervene	System	**System**	Human driver	Some driving modes
4	HIGH AUTOMATION	Full time performance by human drivers of all the driving tasks	System	System	**System**	Some driving modes
5	FULL AUTOMATION	Full time performance by human drivers of all the driving tasks	System	System	System	**All driving modes**

Figure 4: SAE levels of automation source based and adapted from (SAE On-Road Automated Vehicle Standards Committee, 2014; ERTRAC, 2015)

2.2 THE TECHNOLOGY OF TRUCK PLATOONING

Autonomous and cooperative driving is widely researched and still in development and is currently being tested on public conditioned roads and applied in closed areas on industrial sites. It is still not known yet when autonomous and cooperative driving will happen on a large scale and will take over the entire mobility market but that it will have an impact on the traffic management can be roughly estimated (Fagnant & Kockelman, 2015). First, the various SAE levels are discussed in section 2.2.1. In section 2.2.2 the concept of truck platooning is addressed. The technological description of truck platooning is discussed in section 2.2.3. In section 2.2.4 past and present test pilots are addressed.

2.2.1 LEVELS OF AUTOMATION

The degree of automation can be distinguished in specific levels. The Society of Automotive Engineers (SAE) developed a framework to categorize the different levels of automation. A visualization of the functional classifications among vehicles of the present and near future condition is given in Figure 4. The SAE divided automation in two levels: automation where the human driver still monitors the driving environment and automation in which the system monitors the driving environment and the human driver is requested to intervene or respond in specific traffic situations. Currently, the technology of truck platooning is between phase one and two (Dodemont, 2016). At this moment the development of the vehicle technology is between phase two and phase three (Gleave, et al., 2016). The development of platooning lags in development. This is due to the fact that several manufacturers do not develop the technology together, there is no consensus but also there is no uptake from the market.

Numerous of challenges still need to be overcome before truck platooning is applied on a large scale. The incentives to use this type of vehicle differentiate among the stakeholders. Level 0 and 1 is already on the market and trucks are equipped with LCA, PDC, LDW, FCW, ACC, PA, ACC+Stop & Go, LKA (ERTRAC, 2015; Dodemont, 2016). To apply truck platooning on a large scale first the regulations and laws need to be adjusted and other stakeholders (e.g. distribution companies) need to invest in this type of mobility. The willingness of stakeholders needs to be more urgent (Martens & Beenakker, DAF Trucks and Truck Platooning, 2017). The market introduction and uptake of platooning is important because then platooning will be applied on a large scale.

The aim of this research is to analyze the impact of large scale truck platooning on the traffic flow, efficiency and safety of other vehicles on the road. Mixing platoons with other vehicles can possibly reduce the advantages of platooning (Bergenhem, Hedin, & Skarin, 2012). The interaction between cars and platoons might be influenced by the amount of platoons on the road. To understand the influences of this interaction the platoons are considered as a cooperative system.

2.2.2 CONCEPT OF TRUCK PLATOONING

Truck platoons contains a number of trucks with state-of-the-art driving support systems. The motivation to apply truck platooning on the road is the reduction in fuel consumption and the increase of road capacity and safety. Fuel efficiency can be reached in a platoon because of the reduced air drag force (Al Alam, Gattami, & Johansson, 2010). A platoon can be described as *a cooperative system and the individual trucks are sub-systems* (Bergenhem, Hedin, & Skarin, 2012).

According to Ploeg (2014) cooperative driving can be described as *influencing the individual vehicle behavior, either through advisory or automated actions, so as to optimize the collective behavior* *with respect to road throughput, fuel efficiency and/or safety.* With the development of vehicle technology in road traffic the prediction is that these developments lead to system innovation such as advanced vehicle guidance (Arem, Cornelie, & Visser, 2006). The cooperation between sub systems of a platoon is established by communication. The wireless communication within a platoon is a closed-loop configuration. The vehicle measures the distance d_r to the car in front using radar and communicate the velocity and the acceleration to the preceding vehicle and the head of the platoon using IEEE802.11p. This is the standard communication. The cooperative Adaptive Cruise Control (CACC) functions on this communication (Ploeg, 2014).

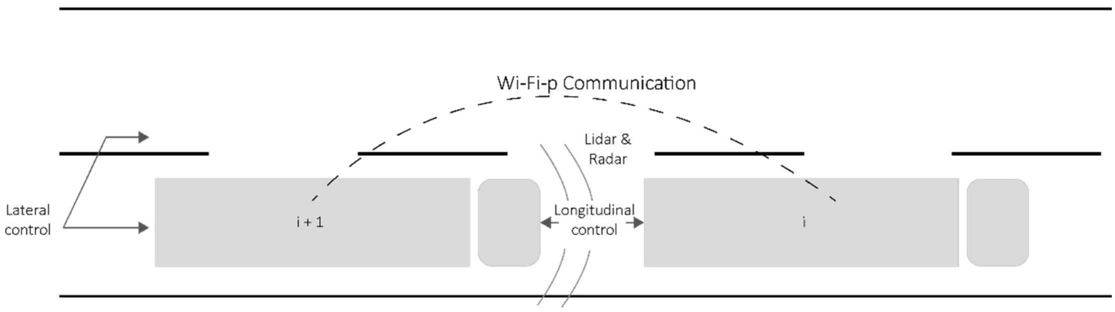


Figure 5: Overview of the concept of truck platooning

The distance between trucks can vary in countries. However, the density on Dutch road is quite high which means the longitudinal distance must be at its minimum (Alkim, Vliet, Aarts, & Eckhardt, 2016). The distance can be as low as 0,3 seconds which is at 80 km/h a distance of 6,7 meters (Janssen, Zwijnenberg, Blankers, & Kruijf, 2016).

2.2.3 TECHNOLOGICAL DESCRIPTION

The dynamics of a vehicle platoon has numerous of factors which influence the driving characteristics of a platoon. The objective of each vehicle in a platoon is to follow its preceding vehicle at a desired distance (Ploeg, 2014). The desired distance $d_{r,i}$ for a vehicle platoon is formulated by the following equation 2.1 (Ploeg, 2014):

$$d_{r,i}(t) = r_i + hv_i(t), i \in S_m \qquad (2.1)$$

The time gap is defined by h, and r_i is the standstill distance. The spacing policy enhances the road safety and improves the string stability. Human drivers are influenced by velocity variation and can possibly overreact on these fluctuations. If a platoon is disturbed by merging of a non-platoon member in a platoon than trucks within a platoon calculates a new distance between the platoon member and non-platoon member. The platoon will drive with a ACC.

A platoon is longitudinal controlled. The longitudinal control is based on the inter truck distance, radar, lidar[1] and inter vehicular communications. The radars and lidars work as an obstacle detection. The longitudinal control, string stability, is important when truck platoons are applied on public roads and need to interact with other vehicles. The application of Adaptive Cruise Control (ACC) is a solution to automatically adapt the velocity of a vehicle to the desired distance to the preceding vehicle. If there is no preceding vehicle the desired velocity is adapted. With ACC the inter vehicle distance and the velocity is measured by radar and lidar. However, it is considered as

[1] Lidar definition: Light Detection and Ranging distance sensor. This is used to measure the distance in longitudinal direction and the lateral offset to the preceding vehicle (Alfraheed, Dröge, Klingender, Schilberg, & Jeschke, 2011).

a comfort system (Ploeg, 2014). Reduction of fuel consumption is beneficial when short inter vehicle distance are established below 1 second (Alam, Besselink, Turri, Martensson, & Johansson, 2015). With ACC these small time gaps cause disturbances in the upstream direction (Ploeg, 2014). To mitigate these disturbances string stability is important. Cooperative Adaptive Cruise Control (CACC) can achieve this string stability for time gaps smaller than 1 second and is an extension of ACC. String stability can be describes as *the attention along the string of vehicles of the effect of disturbances, such as initial condition perturbations or unexpected velocity variations of vehicles in the string* (Ploeg, 2014). In a platoon string stability is an important condition which need to be met in order to establish the safety, driver comfort and scalability in relation to the length of a platoon.

Cooperative driving can be extended by lateral control (Ploeg, 2014). Lateral control involves the steering of the vehicle. It keeps the vehicle in the center of the lane (lane keeping maneuver) and steers the vehicle into an adjacent lane (lane-change maneuver) (Khodayari, Ghaffari, Ameli, & Flahatgar, 2010). The lane keeping maneuver is a combination of the longitudinal and lateral control. Lane detection is the most important part of this type of motion. This system must be able to pick up all types of markings from the roads and filter these to produce an estimate of the vehicle position and trajectory relative to the lane itself such as curvature and width (Khodayari, Ghaffari, Ameli, & Flahatgar, 2010). Two main approaches can be described for lateral control: look-down and look-ahead reference system. Look-down systems follow wires of magnets embedded in the middle of the lane or the infrastructure-guided lane-change scenario. Additional markers can be installed between the lanes to provide a reference path for automated vehicles at certain locations on highways (Khodayari, Ghaffari, Ameli, & Flahatgar, 2010).

2.2.4 PAST AND PRESENT PILOTS OF TRUCK PLATOONING

The technological developments of truck platooning already dates back to the last century. Numerous developments have taken place in order to optimize the technology behind autonomous and cooperative driving but also some pilot test have been done in order to understand the impact of autonomous and cooperative driving on the urban environment. In California 1986, the first automated platoon of four cars was tested on the roads. The PATH (Partners for advanced Transit and Highways) project resulted in a fixed cars distance of 6.5 meter and depended on radar sensors. The PATH project proposed infrastructure changes; embedded transponders in the road and the usage of dedicated lanes. These changes will result in the technical feasibility of autonomous and cooperative driving. (Bergenhem, Hedin, & Skarin, 2012).

In 2000, the DEMO (the Demonstration 2000 Cooperative driving) was developed and tested on longitudinal and lateral control (Alfraheed, Dröge, Klingender, Schilberg, & Jeschke, 2011). In this project the platoon was able to distinguish between small and large obstacles and drive around them. Within this project, the localization and speed of each vehicle was transmitted by inter vehicle communication. The DEMO 2000 project developed an Energy Intelligent Transport System which aims for the reduction of energy and greenhouse gas emission. In this project the longitudinal distance and lateral control is based on V2V communication. Most of these project tested the communication between two vehicles with different type of technologies. However, the V2I communication and the impact on other road users and the infrastructure was not researched.

The project SATRE (Social Attitudes to Road Traffic Risks in Europe), started in 2009, tested as well truck platooning. A navigation system and transmitter/receiver unit that communicates with the preceding vehicle was used. The aim of this project was to facilitate a safe adaption of a platoon at un-modified public highways. The analysis focused on the interaction of the platoon with other road traffic. The goal of this pilot was that the platoons operate on conventional motorways, in a mixed environment with other non-platoon traffic, and no necessary changes to the road infrastructure (Chan, Gilhead, Jelínek, Krejčí, & Robinson, 2012). The platoons shared the road space with other non-platoon vehicles and there was a possibility that a vehicle could enter the platoon. The result from the pilot showed that such a situation is not encouraged and short-interval distances were applied.

The DARPA Grand Challenge, 2004/2005, was a test pilot that focused on the development of the technology in order to develop a participating vehicle. During this test pilot, a number of technologies were tested; GPS data, identifying objects and utilization in urban driving scenarios. For the future functioning of platoons an understanding of the requirements in mixed traffic needs to be developed. In the next pilots the capability to perceive the environment and to conduct appropriate driving behavior is tested (Özgüner, Stiller, & Redmill, 2007).

The most recent test pilot was the European Truck Platoon Challenge 2016. Six brands of automated trucks (DAF trucks, Daimler Trucks, Iveco, MAN Trucks & bus, Scania and Volvo group) have been driving on roads from several European cities to the Port of Rotterdam in the Netherlands (Alkim, Vliet, Aarts, & Eckhardt, 2016). During the challenge, trucks communicated by V2V communication. The truck platoons were applied to a public unconditioned roads. One of the main expected risk was that the truck platoon is a single vehicle entity and there is an increased chance of disturbance of the traffic flow. The truck platoon could not function optimal in complex traffic locations such as: on- and off-ramps, tunnels, curves etcetera (Alkim, Vliet, Aarts, & Eckhardt, 2016).

2.2.5 LAWS AND REGULATIONS FOR TRUCK PLATOONING

To test truck platoons on public roads the Dutch government is adjusting their policies to test truck platooning. In the Netherlands the policy ‘expectable vehicles’ is adjusted and allows companies and institutions to test autonomous and cooperative driving on public roads on a larger scale (Ministerie van infrastructuur en milieu, 2015). Currently, this law ensures that the human driver does not need to drive actively. However, the hands of the human driver still need to be kept on the steering wheel to ensure that the human driver can respond in a short time. The Dutch government is active on a national and international level to allow autonomous and cooperative driving and truck platooning on the road. Testing is possible for companies but certain policies and procedures need to be followed (Ministerie van infrastructuur en milieu, 2015). Adjusting policies and procedures is not enough, the willingness from distribution stakeholders needs to be enhanced as well (Martens & Beenakkers, Truck platooning, 2017; Hottentot, 2017).

2.3 THE ENVIRONMENT AND TRUCK PLATOONING

Truck platooning will have certain advantages for the transportation sector in relation to greenhouse gas emission, fuel consumption, congestion and safety (Sugimachi, Fukao, Suzuki, & Kawashima, 2013; Sadayuki, 2013). Trucks are a key element of the nation’s economy and have an impact on the traffic management and performance (Peeta, Zhang, & Zhou, 2005). The motivation of the potential of heavy vehicle automation concepts is largely economic, promised increasing productivity, decreased fuel consumption and minimize losses due to avoidable crashes

(Nowakowski, Shladover, & Tan, 2015). The following sections give a short explanation on the benefits of truck platooning.

2.3.1 FUEL CONSUMPTION

One advantages of truck platooning is the decrease of fuel consumption. Fuel costs are for an European haulage company of a heavy duty vehicle (HDVs) around 35% of the operating cost. Additionally, the price of oil is expected to rise approximately 60% by 2050 with respect to 2010 (Alam, Besselink, Turri, Martensson, & Johansson, 2015). Therefore, vehicle manufacturers and the transportation industry are developing new methods to reduce fuel consumption: efficient combustion engines, fuel efficient tires, weight reduction and alternative fuels. Numerous researches already analyzed the benefits of truck platooning in relation to fuel consumption. According to Alam et al. (2015) all new technological developments in the field of transportation have the potential to reduce fuel consumption of HDVs by 30%. All these developments are focused on single vehicles.

Fuel consumption depends on the distance between trucks and the speed of a platoon (Larsson, Sennton, & Larson, 2015). Thus, platooning is profitable under specific conditions. The formation of platoons interact with inter vehicle distances which decreases the air drag of the platoon. Figure 6 gives an overview on what kind of effect platooning has in relation to the air drag compared to the leading and following vehicles. It is clear that the overall air drag is reduced of a three truck platoon. Hence, the total air drag is reduced, which reduces the fuel consumption.

Platooning and a short inter vehicle distance can reduce the overall fuel consumption and this can decrease the environmental footprint of the transportation sector. Numerous of factors are of influence on the fuel consumption: weight of trucks, increase of alternative fuel consumption and new materials to build trucks (Heywood, 2010). The last decade the deployment of new vehicle technologies has emerged. According to Heywood (2010), the long-term trajectory of fuel use for trucks is influenced by the market acceptance, high consumer demands and expectation, high manufacturing costs and the time scales by which new technologies can have an impact on the fleet fuel. The technology implementation in the vehicle market has approximately a time scale of 1.5 years. The growth in deployment rates of major new technologies in the past are typically around 1%. The growth of a new technology in the vehicle market is around 5 - 10 years (Heywood, 2010).

Truck platooning can reduce the fuel consumption. However, it should be taken into account that this new type of vehicle technology is influenced by various factors. This can have an impact on the estimate of the time when new vehicle technologies will occur. The market share of a specific technology requires a long acceptance time. The usage of alternative fuels and electric vehicles might increase which can have an impact on the costs of alternative fuels and these type of vehicles. Thus, with the current developments, platooning can reduce the fuel consumption which reduces the air drag and decreases the costs of the fuel consumption. However, with a new technology and its benefits new challenges might arise in relation to fuel consumption, costs, economy and acceptance.

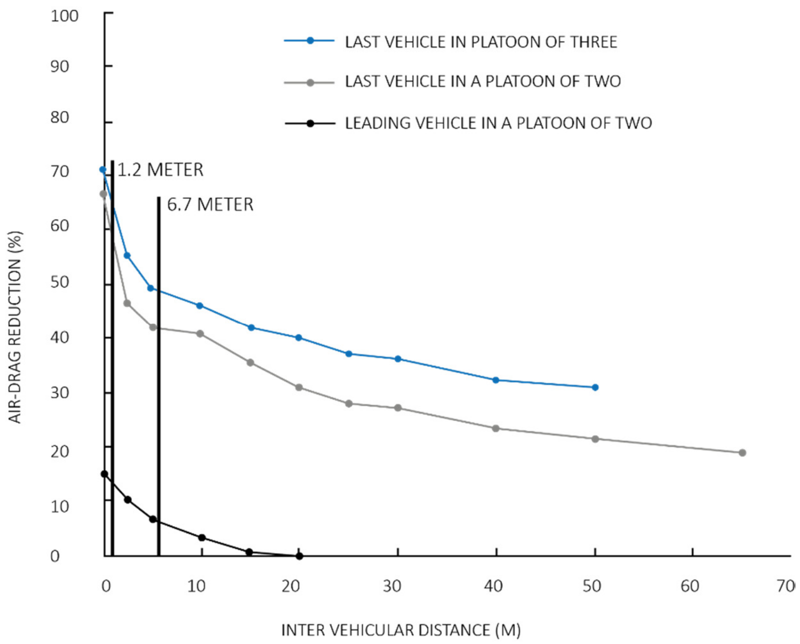


Figure 6: Air-drag reduction for buses in a platoon of 80 km/h. The figure is adapted from (Alam, Besselink, Turri, Martensson, & Johansson, 2015)

2.3.2 ROAD SAFETY

Truck platooning can increase road safety (Alkim, Vliet, Aarts, & Eckhardt, 2016). The human error is responsible for more than 90% of traffic accidents (European Truck Platooning, 2016). In the Netherlands there is an increase of 20% on mobility in the last 10 years (Rijksoverheid, 2008). With the increase of mobility traffic conflicts can occur more and the overall traffic safety can decrease. In 2015, traffic conflicts increased with 9% compared to the year 2014 (CBS, 2017). The prediction is that until 2020 the mobility in the transport sector will increase from 15% up to 80% (Rijksoverheid, 2008). This can results in more traffic conflicts and reduce the safety. Truck platoons are equipped with Wi-Fi-p, radar and camera systems. It is expected with these onboard technologies traffic accidents will decrease. With all these technological aspects the trucks can react in real-time. When a first truck brakes, all the following trucks will break in real time. The reaction gap is almost near zero. The inter vehicle distance between trucks is shorter and the trucks will drive at a constant speed. Additionally, acceleration and braking is synchronized and trucks will not overtake each other (European Truck Platooning, 2016; Jongenotter, 2016). This can increase the traffic flow on the road as well as the safety.

Traffic safety depends on numerous of factors and one of the factors is time-to-collision. Road collision can be divided in two categories: human and engineering (Michalaki, Quddus, Pitfield, & Huetson, 2016). Engineering factors are related to infrastructure characteristics and traffic conditions and human factors are related to driving groups, gender, psychological state. Collision can occur frequently when vehicle speed varies, high percentage of HDVs, fatigue of the human driver.

According to Alian et al. (2016) road safety is affected by the driver behavior, road geometry (quality of infrastructure), traffic conditions (e.g. traffic flow and speed) and lighting conditions. The aim of this research was to evaluate interaction between changes in road geometry and behavioral responses to these changes. The results showed that there are complex interactions between geometrical and behavioral constraints on driver information. However, the relation between driver behavior, road safety and environmental conditions and the interaction between those three needs to be further analyzed.

Alam et al. (2011) used a game theory to establish safety criteria for HDVs platooning applications. In this research two identical vehicles where simulated where the vehicles only received the information about the relative position and velocity of the immediate vehicle ahead. This research concluded that an inter vehicle distance of 1.2 meters can be obtained for two identical vehicles without endangering a collision and that the trucks can operate safely. Additionally, if the wireless communication between trucks is further improved the distance could be even less.

The velocity of a platoon needs to be stable in order to stabilize the gap size, the drivers comfort and the driver's confidence in the system. This is also important to achieve the best fuel consumption (Chan, Gilhead, Jelínek, Krejčí, & Robinson, 2012; Al Alam, Gattami, & Johansson, 2010). Nonetheless, recent studies showed that drivers begin to feel uncomfortable at following gaps less than 15 meters and feeling unsafe at gaps of less than 7 meters (Nowakowski, Shladover, & Tan, 2015). Additionally, the drivers takeover time to effectively intervene to avoid a crash is nearly impossible with a inter vehicle distance of 10 meters (0.35 seconds).

2.3.3. ROAD CAPACITY

The inter vehicle distance of truck platoons can be set on 10 meters and even 6.7 meters. With this inter vehicle distance the truck platoons can contribute to an optimization of traffic flow up to 9% (Trantow, Stieger, Hees, & Jescke, 2013). This will lead to vehicle occupancy and gained road space. Road capacity can be reduced by lane changing, moving bottlenecks, large vehicle density and aggressive lane change (Li & Sun, 2017). Change in road geometry and moving bottlenecks can influence the vehicle interactions when vehicles are executing a lane change.

According to Lighthill and Whitham (1955) there are fundamental relationships among traffic density, flow and average speed. These relationships describe how various parameter of traffic flows vary over time which help determine the capacity of the roadway. They stated that there are external influences which have an effect on the traffic flow and there are some vehicle factors within traffic which affect the capacity and safety. These factors are individual speeds, braking capabilities and driver behavior.

2.4 DRIVING BEHAVIOR AND TRUCK PLATOONING

The technological development of truck platooning is still in development. Truck platooning adds not only to new driver requirements but also requires considerations about the operation of the platoon and its impact on its surrounding environment. The questions that arise *are: how many trucks should be allowed in a platoon? And how will it affect the traffic, vehicle movements and the comfort levels around them?* (Nowakowski, Shladover, & Tan, 2015). Human mobility is embedded in a social as well as in technological environment (Michon, 1985). It is important that the social impact and the user behavior in relation to truck platooning is analyzed and investigated. Two important issues related to road safety is the acceptance, driving behavior and the situation awareness.

2.4.1 HUMAN FACTORS AND TRUCK PLATOONING

New vehicle technologies can have an impact on specific human factors and the overall performance of vehicles within the traffic flow. New human factors issues can be raised when humans will delegate specific driving tasks to systems (Pauzie & Orfila, 2016). These new human factors issues are the following:

- Acceptability: This is a severe challenge which influences the success of the implementation and to enhance the benefit of these systems;
- Trust: key variable and has an impact on the acceptance of automated systems;
- Situation awareness: analyzing the surrounding and understanding specific situations;
- Mental workload: psychological construct.

Partially and full automated vehicles will have an impact on specific human factors and workload and situation awareness are two of the most important for the performance and safety. Situation awareness is affected by various factors such as weather conditions, in-car tasks, height differences in road geometry, psychological status of drivers etcetera. Driving behavior in autonomous and cooperative vehicles and in manually driven vehicles differ from each other. The takeover time in highly automated vehicles takes approximately 1.9 seconds up to 25.7 seconds (Eriksson & Stanton, 2017). With a transition phase from manual to highly automated this can cause an increase in traffic conflicts.

2.4.2 DRIVING BEHAVIOR

With ACC, CACC, navigation systems, in-vehicle and road side information the role of the driver becomes more complex. The driver becomes the manager in the car (Hoogendoorn, van Arem, & Hoogendoorn, 2012). When truck platoons are applied to the A15 these platoons require interaction with surrounding traffic and human drivers. This influences how well a truck platoon performs on the road and also the driving behavior of other road users. Driving behavior is an important element of microscopic models. Driving behavior at merging sections affect traffic operations and is the cause of breakdowns (Marczak, Daamen, & Buisson, 2013).

With the implementation of truck platoons the impact of the truck behavior in the current traffic flow is minimized. However, with the implementation of truck platoons in the current traffic flow new matters will arise. To understand the impact of truck platoons at the A15, a closer look has to be given to the driver behavior standpoint. According to Wegman (2016) driving behavior and the safety of road users is subjected to numerous of factors: age, driving experience, psychological state, various types of road users. The human is the measure of road management but the human measurement is not overall the same.

Driving behavior is a complex phenomenon. One of the manoeuvers that has an impact on the traffic flow and the driving behavior of other road users is lane changing (merging behavior). Drivers always first scan their surrounding when a certain action is taken according to the drivers preferences. Some parameters of the decision of the driver are the safest, the most comfortable, the first available etcetera. Driving behavior is affected by road infrastructure, physical and social environment (Ram & Chand, 2016). Truck drivers and non-truck drivers can react differently to the routing information provided through an advanced information system. Driver behavior theory is mostly defined with the terms risks and accidents. According to Summala (1996) risk measures are a control variable in driving behavior. A driver is inclined to react to changes in the traffic system and this reaction occurs in accordance with the motives of the driver. These reactions are behavioral adaptions and are called risk compensation. The assumption is that drivers control the safety margins rather than the specific risk measure, and only when the risk is exceeded or expected to be, the behavior was influenced (Summala, 1996).

Hoogendoorn et al. (2012) analyzed the influence of the complexity of the driving task on longitudinal driving behavior. A new mathematical framework was proposed to understand the driving behavior complexity. This research divided the drivers behavior in compensation effects and performance effects. The compensation effects are described as the assumption that drivers regulate their driving in order to compensate for any reduction in attention to the driving task. Compensation effect are reduction of speed and changes in distance to the lead vehicle. Through the driving simulator it was established that the complexity of driving task has a substantial influence on empirical longitudinal driving behavior.

Fuller (2005) developed a general theory of driving behavior with a task capability interface (TCI), which describes the dynamic interaction between the determinants of task demand and driver capability. Driving tasks are influenced by interacting elements such as road alignment, road marking, other road users with various properties occupying critical areas in the project path of the driver. Driving behavior is an interaction between the driver and the driving situations. When certain driving tasks are executed an information flow is needed that will result in attention, perception and decision making.

Ossen and Hoogendoorn (2011) showed in their research that truck drivers have a more robust car following behavior than passenger car drivers. The aim of their research was to gain insight into the level of heterogeneity in car-following behavior in real traffic (Ossen & Hoogendoorn, 2011). The results of this research showed that truck drivers drive in general with a constant velocity compared to passenger car drivers. In addition, the desired time headways of passenger car drivers are smaller by trucks than another passenger car.

According to Ferrari (2009) the interaction between trucks and cars is asymmetric. Trucks differ in size, weight, lateral control and it is hard to change direction immediately. Trucks create a reduction in the vision of car drivers. The cause of stress of human drivers is associated with large trucks and the effect what the vehicle size has on the visibility (Ferrari, 2009). Thus, the heterogeneity of flows does not cause any damage to trucks, but it makes driving in cars more difficult and dangerous due to the large size trucks which reduces vision to car drivers.

Durrani et al. (2016) estimated the parameters of a vehicle-following model for cars and HDVs separately. Additionally, they researched the driving behavior differences in the way cars and HDVs follow each other based on the estimated parameters. A microscopic model, VISSIM, was used to simulate the following and driving behavior of the various vehicle categories. The parameters were based on the Wiedemann's 99 vehicle-following model. Three vehicle-following cases were formulated: car following car, car following heavy-vehicle, heavy vehicle following car. The results suggested that vehicle-following behavior is significantly different among the different vehicle categories and with the different vehicle following cases. Compared to the car, following heavy vehicles kept a longer safety distance and longer maximum spacing during following, took more time to decelerate to safety distance, were less sensitive to the lead vehicle behavior and had a more stable velocity (Durrani, Lee, & Maoh, 2016). These results were also observed with the case heavy vehicles following cars and cars following heavy vehicles. Between the three cases there were behavioral differences. The vehicle size affected the following vehicle consciousness and the overall sensitivity to the lead vehicle's behavior. This research stated that driving behavior parameters should be specified for the different vehicle classes as well as the vehicle-following cases.

2.4.3 MERGING BEHAVIOR AT ON- AND OFF RAMPS AND WEAVING SECTIONS

Merging can have an enormous impact on the traffic flow. The quantitative understanding of the impact on the traffic flow is still elusive. Merging behavior acts as a moving bottleneck and is a disruption which can trigger other lane changes (Laval & Daganzo, 2006). Near an on- and off ramp the merging interaction between trucks and other road users is important. Previous research of logistic force has shown that the biggest irritation among truck drivers is the sudden lane changing behavior of other road users to access the off ramp. This will cause road accidents. Human drivers respond, intuitive, to certain traffic conditions. Human drivers need to understand their surroundings in just a few seconds. Non-platoon drivers can accelerate or deaccelerate and merge into a platoon even if the gap is not suitable for merging (Jongenotter, 2016). This type of merging behavior can have an effect on the traffic flow and safety.

Marczak et al. (2013) developed a model to understand the gap acceptance and rejection based on the longitudinal position, the length of the gap and the difference in speed of the three vehicles involved during a merge: the putative leader, the putative follower and the merger. A stochastic model is developed to analyze gap rejection and acceptance. This research defined several parameters which needs to be taken into account when merging behavior is studied (Figure 7).

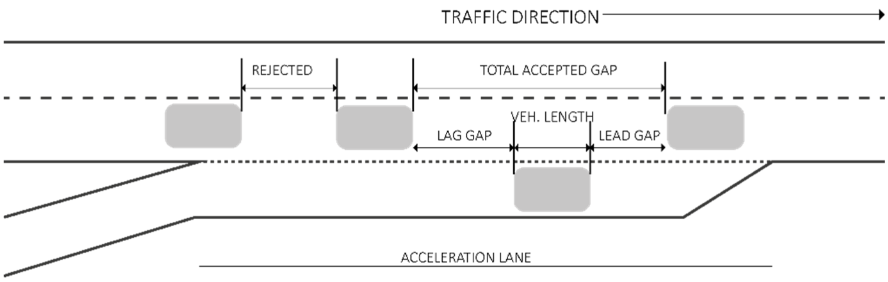


Figure 7: Merging behavior vehicles. Figure is retrieved and adapted from (Marczak, Daamen, & Buisson, 2013)

The merging parameters courtesy lane changing is not taken into account because this can be hard to observe. In the Netherlands drivers accepted smaller gaps where the congestion level was lower than in Grenoble, France. The acceptation of a gap is defined by the length of the possible gap.

Traffic can be disordered at weaving sections (Liu, Li, & Jia, 2014). Liu et al. (2014) investigated the influence of the intensity of two vehicle types on a weaving section: cars and trucks/busses. Most weaving sections are joined together by an auxiliary lane, which is adjacent with the main road (Figure 8). Congestion and traffic jamming can occur upstream the weaving section and free flow exists downstream the weaving section.

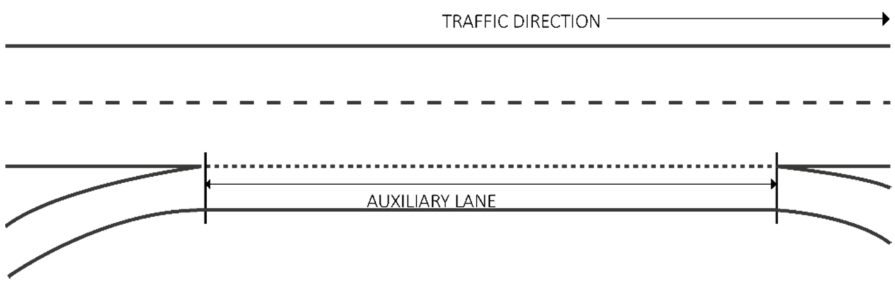


Figure 8: Example of a weaving section that is common on highways. The figure is adapted from (Liu, Li, & Jia, 2014)

The traffic dynamics of the weaving section differ compared to other traffic locations. Liu et al. (2014) showed that when the proportion of buses increases there is more fluctuation in the weaving behavior. These fluctuations are also caused by large on-ramp entering vehicles. The weaving behavior is disturbed by large and slow vehicles. This research showed that traffic strategies near weaving sections need to pursue on eliminating the traffic disturbance by separating large, slow vehicles.

Traffic safety varies within different traffic locations. One of the traffic conflict areas is a weaving section of freeways. Little research have been done to the relation of traffic safety and weaving sections. Vehicles merge and diverge in a close proximity and need to execute one or more lane changes at a weaving section (Golob, Recker, & Alvarez, 2004). Golob et al. (2004) analyzed three type of weaving sections to examine what type of road accidents occur and which different aspects of safety leads to implications for traffic improvements. According to this research weaving section accidents are more likely to involve vehicle lane changes, because merging and diverging is one of the common characteristics of weaving sections. Additionally, accidents within weaving sections more likely occur due to failure to yield or dangerous driving. The results showed that most significant influences of collision were related to the type of movement performed by the vehicles and the exact location where the incidents take place. Sideswipe collisions have the highest likelihood of occurrence in weaving section and this type of collision occurs the most in the interior lane (Golob, Recker, & Alvarez, 2004). To enhance the traffic safety of weaving sections drivers need to be warned sufficiently when they need to change lanes, drivers need to be educated better, speed restrictions should be addressed and a sign of potential hazards could be applied.

2.4.4 DRIVERS ACCEPTANCE

The transport system is complex and knowledge about user acceptance is valuable for understanding the human behavior in complex environments (Burnett & Diels, 2014). Acceptance can be defined as the requirements and needs that persons need in order to analyze their own environment and the willingness to use (Burnett & Diels, 2014). This research will focus not on the willingness to use but on the requirements and needs.

Truck platoons is a new type of mobility and can have an effect on the perception of driving of other road users. Applying truck platooning on public roads creates a new set of driving conditions for non-platoons road users (Burnett & Diels, 2014). If truck platooning is applied on a large scale, will this result in behavioral adaption whereby the road user consciously or unconsciously also adopt shorter time headways adopted in platoons? (Burnett & Diels, 2014).

Technology in the automotive environment is rapidly increasing and at the same time the number of older drivers on roadways is increasing (Owens, Antin, Doerzaph, & Willis, 2015). Driving behavior can be more difficult due to the fact that older drivers already experience perceptual, physical and cognitive challenges. New vehicle technologies and in car technologies can be of influence on the driving behavior of this specific generation. The older generation responded their concern with safety. Vehicle needs and unique driving is emerging and large scale implementation of vehicle systems need to incorporate these factors in their vehicle technology design and supporting infrastructure.

2.5 INFRASTRUCTURE SUPPORT FOR TRUCK PLATOONING

Previous pilots of platooning show that risky traffic locations needs to be optimized in order to facilitate truck platooning. To guarantee safety and optimize the traffic flow, infrastructure support and specific road strategies can be a solution to facilitate truck platooning. According to Ran et al. (1999), infrastructure can obtain information on vehicles' position and speed as they approach the merge point and uses this information to analyze the traffic flow near the juncture. Another possibility of infrastructure support is that the infrastructure could issue restrictions on vehicle's movements in the merge area to create or adjust gaps, or guide merging vehicles into existing gaps (Ran, Leight, & Chang, 1999). Platoons need to adjust their speeds, paths, spacing or platoon sizes. Road strategies are applied in the Netherlands in the most effective way (Hoogendoorn, et al., 2012). First, standard road strategies are discussed what the impact is on traffic management. Second, new dynamic strategies that are proposed by the available literature is addressed.

2.5.1 PAST AND CURRENT APPLIED ROAD STRATEGIES

According to Xun et al. (2011), a dedicated lane for trucks can enhance the efficiency, safety and traffic flow. The aim of this research was to analyze the impact of a dedicated lane on traffic flow and travel time by simulation. Lane-changing is one of the main factors in traffic accidents. The safety performance of a multilane freeway shows that there is an increasing number of lanes associated with a rising number of lane-change related conflicts and opportunities. The amount of lane changing will decrease if a dedicated lane is introduced. The results shows that a dedicated lane result in a decrease of travel time and enhanced safety (Xun, Tomio, & Takayuki, 2011 11(3)).

Wu et al. (2007) analyzed the ramp metering strategy on acceleration/deceleration rates, speed and the acceptance gap. Ramp metering can improve the merging conditions of traffic an entrance ramp, but may cause minor reduction of speeds of traffic. Ramp metering uses traffic signal at on ramps to regulate the flow of vehicles entering a congested highway and prevent congestion and flow breakdown. The conclusion was that ramp metering does not have a significant evidence that the system will smooth the traffic flow downstream. However, ramp metering resulted in easier merging conditions at the entrance ramp.

Özgüner et al (2007) discussed the automotive technologies and their present capabilities. An analysis has been done on the DARPA Grand Challenge in order to understand the benefits and challenges of automotive technologies on infrastructure. Autonomous and cooperative driving needs sensing enhancement through V2V and V2I communication but also by a cooperation between environment and the vehicles. An example of infrastructure development is a series of magnets 'slots' placed on the highway lane to orientate the vehicles along the road and provide information about the curves. Another infrastructure based technology is RFID tags that can be placed on the roadways. These RFID tags can be placed on motorways, intersections to provide information about the traffic environment.

2.5.2 DYNAMIC ROAD STRATEGIES

Infrastructure assets are designed to function for several decades (Verlaan & Schoenmaker, 2013). Traffic management and the current practice of it can be viewed in a different way when 'smart' vehicles are applied on Dutch roads. As shown in previous paragraphs mobility is influenced by many factors: human, environment, technology, trends etcetera (Figure 9). Infrastructure adjustments and road strategies need to interact with new technologies. Trends in the automotive sector and societal trends such as urbanization gives an opportunity to evaluate and organize road management in a different and more connected way.

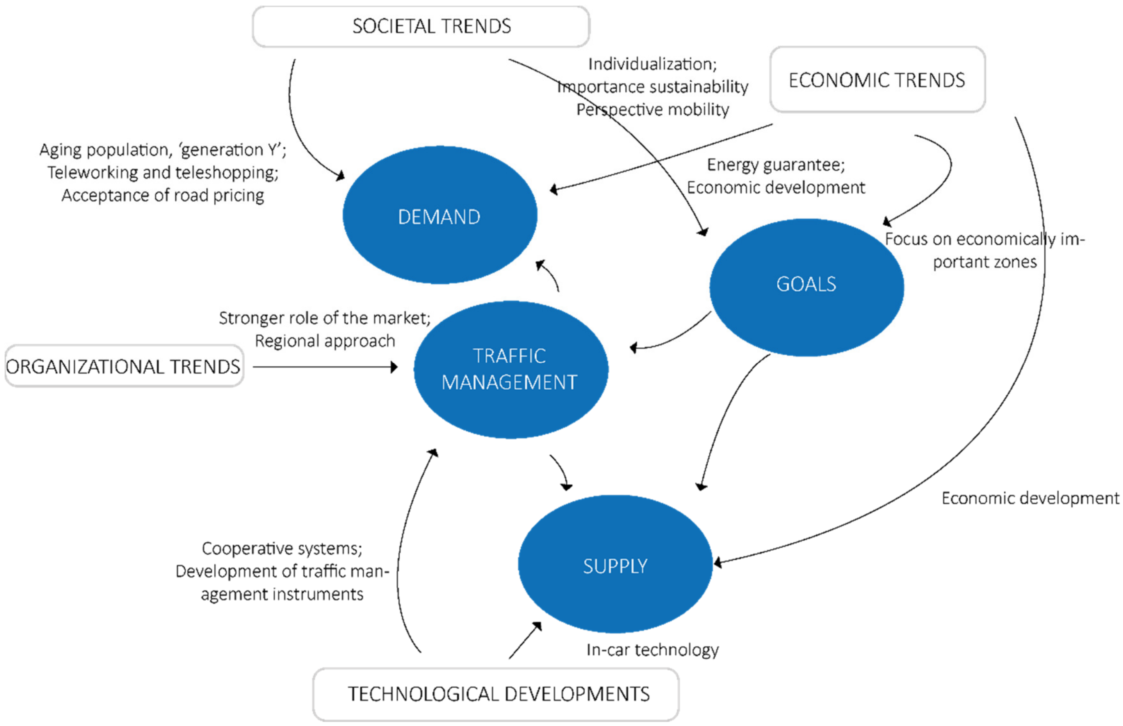


Figure 9: Trends in the mobility sector which are of influence on the traffic management (Hoogendoorn, et al., 2012)

In the Netherlands road strategies and adjustments are subjected to the regulation stated by public bodies e.g. government, department of transportation. Traffic safety is developed by the Sustainable Safety Approach. With this approach road authorities want to eliminate or considerably reduce serious injuries through the use of safe systems architecture and designing new parts of the infrastructure (Wegman, 2016). This approach operates on six points:

1. *Ethical;*
2. *Proactive approach:* Use and adapt knowledge to local conditions;
3. *People are the measure of things:* Human limitations, capabilities and body are the guiding factors;
4. *Integral holistic approach:* Design systems components are integrated with the whole system;
5. *Eliminating latent gaps;*
6. *It embodies a preventable injuries approach.*

Various road strategies can be applied to increase the traffic safety, flow and efficiency. With new emerging type of mobility the road management can be designed more dynamically. In the Netherlands, various dynamic road solutions are already proposed: ramp metering, dynamic route information, National data warehouse, variable speed limits, plus lanes (dynamic left lane) etcetera. The various road adjustments that are proposed in previous researches are quite obvious. Constructing new roads, widening existing roads and improving bottlenecks are approaches that are effective and problem solving but this is sometimes just temporary (Hoogendoorn, et al., 2012). With new vehicle technologies arising new, dynamic road strategies can be applied. Possible other solutions to increase traffic flow, efficiency and safety are: management or controlling the speed of traffic, improving the safety of vehicles or improving the safety of the roadway infrastructure. Traffic management and road strategies need to be more flexible in handling changes in supply and demand and must be coordinated and used across the network. The traffic management should shift from passive to proactive to achieve a range of objectives (Hoogendoorn, et al., 2012). Integration of roadside and in-car systems to optimize the monitoring and management of traffic (Hoogendoorn, et al., 2012). Currently the communication by road authorities is organized through roadside systems. New mobility systems can be combined with traffic data obtained by roadside measurements. A closer look has to be given to the demand and supply on the roads (Figure 9).

According to Hoogendoorn et al. (2012) the flexibility can be increased on the supply side. Currently this is regulated by ramp metering, peak and plus lanes and this can be deployed more intelligently. An information-ergonomic approach should be followed to develop a safe and user friendly system. This can be done by (Hoogendoorn, et al., 2012):

- *Optimize for Multiple Policy Goals*: road strategies should be optimize not only on travel time or traffic flow but it is also needs to consider safety and quality of life (noise, energy consumption);
- *Integrated approach*: Traffic management should be integrated with traffic management, infrastructure planning and spatial planning;
- *Organization*: Regional cooperation can be strengthened further. Additionally, clear agreements should be made.

In the Netherlands slower vehicles are assigned to the right lane. HDVs travel longer distances. Cars have a shorter path to their destination and tent to go on and off a highway quicker. A possible road strategy could be of changing trucks to the leftmost lane (Jongenotter, 2016; Hoogendoorn, et al., 2012). HDVs and cars have a different type of travel behavior. The Dutch road management is organized in such a way that slower vehicles use the right lane and a vehicle with a higher speed uses the left lane. The infrastructure in the Netherlands can be used more efficient by applying the vehicles with the longest distance on the left lane and vehicle with a shorter destination at the right lane.

According to Ploeg (2014) current advanced driver systems still aims for optimizing the individual vehicle. To optimize the road traffic system as a whole real time information on other road users is generally required. A wider information horizon needs to be created for cooperative vehicles. For successfully integrate cooperative vehicles a deployment of traffic services and vehicular functions and services needs to be established. Cooperative driving depends to a large extent on information exchange and this can be achieved by other road users or roadside units. However, there has to be a level of consistency for road users and roadside units to support cooperative behavior (Ploeg, 2014). By wireless communication data can be exchanged from V2V and V2I. Wireless communications are subjected to failure and need to be designed with a certain robustness.

Thus, a careful balance is needed for wireless communication systems. Infrastructure support can be beneficial for truck platooning. One of the applications is a variable speed distribution. Near merging, diverging and weaving areas vehicles are informed that the overall speed needs to be reduced to efficiently drive through the network in a safe manner. Another application can be dynamic merging and diverging lanes. Plus lanes are already introduced in the Netherlands. These lanes will only be used by vehicles when the capacity on the road is at its peak. This type of road strategy can also be applied in complex traffic locations.

2.6 CONCLUSION

Lots of research studies are available in the field of platooning technology and driving behavior. However, little studies connect these two research areas. Excessive traffic can lead to the reduction of the benefits of truck platooning (Larsson, Sennton, & Larson, 2015). There is a research gap between the translation of the technology of truck platoon to the behavior of vehicles on the infrastructure. With the application of large scale truck platoons it is possible that the benefits cannot be met and only leads to negative effects such as: decrease in traffic safety and no reduction in fuel consumption.

The advantages of truck platooning depends on the inter vehicle distance, stable connection between trucks, air drag reduction, weight, speed etcetera (Fagnant & Kockelman, 2015; Ploeg, 2014; Alam, Besselink, Turri, Martensson, & Johansson, 2015). Currently, the Dutch government is adjusting laws and regulation to allow tests with platoons on the Dutch infrastructure. One of the main advantage of truck platooning is the reduction in fuel consumption with a small inter vehicle distance which also increases the overall road capacity. Therefore, to analyze what the impact of large scale truck platooning is on the traffic management on the Dutch infrastructure an inter vehicle distance of 6.7 meters (0.3 seconds) is used. Additionally, various test (Alkim, Vliet, Aarts, & Eckhardt, 2016; Chan, Gilhead, Jelínek, Krejčí, & Robinson, 2012; Alam, Besselink, Turri, Martensson, & Johansson, 2015) have taken place with a platoon consisted of three trucks. The interaction between trucks and cars is asymmetric. Vehicles are influenced by the size and length of a truck as well as the road geometry. Complex traffic situation such as weaving and merging this asymmetric relation can be influenced by the length and short inter vehicle distance of a platoon. Drivers behavior of vehicles is influenced by the human and engineering factor. To understand the impact of large scale truck platooning the engineering level is taken into account. The behavior of vehicles can be generalized in complex traffic situation. The human factor is not taken into account in this research because drivers behavior differs per person, day, age etcetera.

Thus, the following assumption from the literature study are taken into account in this research

- Truck platoons consisted of three trucks with an inter vehicle distance of 6.7 meters;
- Congested areas can decrease the benefits of platoons such as traffic safety and efficiency;
- Vehicle behavior can be influenced by vehicle size and length;
- The ratio of trucks on the road have an influence on performing lane changes of vehicles;
- Fluctuations in traffic behavior (acceleration and deceleration) decreases the traffic safety;
- Complex traffic locations are merging and weaving areas.

Traffic management is designed according to specific guidelines. The main focus of traffic management is related to the safety of the users in the traffic system. Platooning is a new type of mobility and the prediction is that it increases traffic safety and the road capacity. To create a safe and sustainable traffic management system the impact of platooning can be analyzed on the traffic flow, efficiency and safety. Table 1 gives an overview of literature that addresses possible road traffic management strategies.

Table 1: Overview of possible road strategies in order to enhance truck platooning

Literature	Road Strategy	Subjected to trends	Advantages
(Jongenotter, 2016; Hottentot, 2017)	Trucks drive on the outermost left lane	Yes	Lane changing is not influenced by truck platoons
(Hoogendoorn, et al., 2012)	Proactive and dynamic road strategies	Yes	Can react on trends and new developments in technology
(Ploeg, 2014)	Connecting traffic data with in-car systems	Yes	Create a safe driving environment

2.7 DISCUSSION

Truck platooning is a widely researched new mobility application. To implement truck platooning on the road some challenges still need to be overcome on an economic, technological, vehicle driving behavior and infrastructure level.

The inter vehicle distance of a platoon is set on 6.7 meters. This is an optimum and cannot be met. Current testing with platoons set an inter vehicle distance of 15 - 20 meters (European Truck Platooning , 2016). Additionally, test pilots showed that the communication between vehicles in complex traffic situations is still not optimal. The human driver needs to overtake driving tasks from the system. Drivers behavior is subjected to numerous variables. This research will only take the engineering factors into account. Traffic safety can also be analyzed by the human factor in the traffic system.

The next step to fill in the research gap and make a first attempt to connect the large scale application of truck platooning to driving behavior on the Dutch infrastructure. In the previous paragraph specific assumptions have been made to predict the impact of platooning. These assumption can be considered as the optimum. Nonetheless, it can indicate what the impact of platooning on traffic management is and what can be done with the traffic management to enhance truck platooning.

CHAPTER 3

RESEARCH METHODOLOGY: MICROSCOPIC TRAFFIC SIMULATION

Modeling is a way to solve problems that occur in the real world and can be done when experimenting in the real world is impossible or expensive. Simulating can be executed on three levels: macroscopic, microscopic and mesoscopic. To analyze the impact of truck platooning on the driving behavior of other road users and the traffic efficiency, flow and safety the microscopic software VISSIM is used. VISSIM consists of a driving behavior model where the driver behavior is based on specific algorithms. The driving behavior of truck platoons can differ from other trucks. Therefore, specific set of rules are defined in order to simulate the behavior of truck platoons.

Section 3.1 addresses the various microscopic simulation levels which can be used. Second, the various microscopic methodologies are described. The advantages and disadvantages of microscopic modeling are addressed in section 3.2. The microscopic simulation software VISSIM is discussed in section 3.3. Section 3.4 gives a short elaboration on the implementation of traffic safety within microscopic modeling. The validation and calibration process of simulation methodologies is discussed in section 3.5. The concern in relation to microscopic modeling are addressed in section 3.6. To conclude, a simulation model methodology is proposed in section 3.7 which will be used to execute this research.

3.1 INTRODUCTION

New mobility concepts could improve the traffic flow, safety and other important factors. Many practical issues need to be overcome and realistic and efficient traffic simulation models need to be constructed. Traffic modeling is an important aspect of transportation research (Gora & Rüb, 2016). These simulations are helpful to understand the impact of certain traffic strategies that are applied and to identify bottlenecks in the system. Traffic simulation models have the ability to describe the observed spectrum of a non-linear phenomenon and their characteristics (Naiem, Reda, El-Beltagy, & El-Khodary, 2010). Traffic simulations can be modeled according to various approaches and principles depending on the modeler's purposes (Barcelo J. , 2010). Simulation models do not represent real driving behavior in certain traffic situations. Simulation models give an approximation of how vehicles interact when traffic characteristics are changed.

Traffic simulations can be divided into microscopic, mesoscopic and macroscopic levels (Papathanasopoulou, Markou, & Antoniou, 2016). Macroscopic simulations are based on the principle that traffic flows are a fluid process whose state is characterized by the macroscopic variables: density, volume and speed (Barcelo J. , 2010). Microscopic simulations describe the fluid process from the dynamics of individual particles (vehicles, pedestrians etcetera). Mesoscopic models represent a modeling alternative based on a simplification of vehicular dynamics (Barcelo J. , 2010). To simulate the impact of truck platooning on its environment the level of simulation modeling is important. Truck platoons acts as one vehicle entity within a traffic flow. Microscopic modeling is a suitable simulation method to analyze the impact of truck platooning on the traffic management and road safety.

3.2 MICROSCOPIC MODELLING

Microscopic modeling of traffic flows is based on the description of the motion of each individual vehicle composing a traffic stream (Barcelo J. , 2010). Every action (acceleration, deceleration, lane changing) of each driver is modeled in response to the surrounding traffic. Microscopic traffic simulations use a vehicle-following model which predicts the behavior of the following vehicles based on the behavior of the lead vehicles (Durrani, Lee, & Maoh, 2016). The driving behavior is reflected by driver behavior parameters in the vehicle following model.

According to Barceló et al. (2004), microscopic simulations are based usually on the family of car following, lane changing and gap acceptance models to model the vehicle behavior. Microscopic simulations capture not only the dynamics of traffic but these simulations are also capable of using behavior models that can account for drivers; reactions when exposed to Intelligent Transport Systems (Barcelo, Codina, Casas, Ferrer, & Garcia, 2004)..

Fan et al. (2012) developed a microscopic simulation model that takes the driver behavioral characteristics into account at merging areas at highways. The aim of this study was to compare observed conflicts and driving behavior with simulated conflicts and driving behavior. With VISSIM this comparison was tested and several calibrations needed to be done to verify the observed parameters. The results of this study shows that a calibration and a sensitivity analysis can be used to compare and validate simulation conflicts with observed conflicts.

Brügmann et al. (2014) elaborates on the scientific discussion of the ongoing process in the development of traffic simulation modeling. The article states that no microscopic simulation model fits all the needs for the various kinds of vehicular traffic flow (Brügmann, Schreckenberg, &

Luther, 2014). The data information accuracy in microscopic modeling does not always lead to improved output information accuracy. The correctness of a microscopic traffic model needs to be verified by the correctness of each separate part of the model and the output needs to be verified with results of specific literature. Microscopic simulation models rely on the stationary traffic data that in many cases loop detectors will provide. These detector loops can provide traffic measurement from the real world but can also provide traffic information from the simulation system to the users as a feedback mechanism. Thus, it is important the data from the real world detector loops is comparable to what the simulation system provides.

One of the challenges of microscopic modeling is the lack of accurate empirical, in situ data for a detailed analysis for vehicle interactions (Coifman, Wu, Redmill, & Thornton, 2016). In situ data is data which is collected at a specific location. This data is hard to collect. Data collected by detector loops is suitable for microscopic simulation. Loop detectors are capable of monitoring traffic at fixed locations. Microscopic modeling will never be able to capture the driving behavior of the real world. The results of microscopic simulation should be extra carefully analyzed (Papageorgiou, 2006). Complex processes are taking place in the real world and the model's features may be inadequate. However, microscopic modeling can give possible strategies and solution for the infrastructure network.

3.3 TRAFFIC SIMULATION SOFTWARE

One important aspect of transportation engineering is traffic modeling. With these mathematical tools real-world traffic can be described and analyzed. In the last 50 years modeling approaches have been developed to describe the traffic flow. Microscopic modeling has numerous of software applications each with its own characteristics and methodological framework. Dynamic traffic models correspond to the dynamic traffic assignment problem. A few examples of traffic simulation software that is used in numerous research articles are: VISSIM, AVENUE, Paramics, AIMSUM (Barcelo J. , 2010). VISSIM is a behavior based multi-purpose traffic simulator to analyze and optimize traffic flows (Fellendorf & Vortisch, 2010). AVENUE is a hybrid traffic simulation and is used for middle size network (Kuwahara, Horiguchi, & Hanabusa, 2010). Paramics can be used to optimize urban control systems and does not use modeling artefacts (Sykes, 2010). AIMSUM transport simulation software emphasized on dynamic simulation capabilities. AIMSUM is used to solve transportation engineering problems with reference to three real-world examples (Casas, Ferrer, Garcia, Perarnau, & Torday, 2010).

3.3.1 MICROSCOPIC MODELING: VISSIM

According to the literature study, driving behavior can be affected by vehicle size/length and the interaction between cars and trucks is asymmetric. In previous paragraph various microscopic models are addressed and one of these simulation tools is VISSIM. VISSIM is a behavior based simulation tool. The vehicle behavior of cars and trucks can be analyzed for complex traffic network locations. VISSIM allows it user to construct a traffic network based on the actual traffic network and its characteristics corresponding to the real world. Traffic features such as intensity, velocity, acceleration/deceleration behavior, length, look ahead and lookback distance can be described accurately per vehicle type. The aim of this research it to understand the impact of large scale truck platooning on other vehicles in relation to traffic flow, efficiency and safety. The vehicle behavior of trucks and cars differ and therefore VISSIM is suitable as an analysis tool.

Microscopic traffic features within VISSIM can be described accurately. A visualization of complex traffic conditions are possible by the support of realistic traffic models (Fellendorf & Vortisch, 2010). VISSIM can be used for various traffic situations:

- Studies on heavily utilized motorways to identify system performance;
- Development and analysis on management strategies on motorways;
- Studies on arterials with signalized and non-signalized intersections;
- Can be applied in multiple scenarios such as mobility studies, intelligent traffic systems, management systems and traffic control systems.

The applications mentioned here above do not cover all the functions and studies that can be done with this simulation tool and is more extensive than mentioned.

3.3.2 SYSTEMS ARCHITECTURE

VISSIM is a discrete, stochastic, time step based, microscopic model with driver-vehicle units as single entities (Papageorgiou, 2006). VISSIM contains a psycho-physical car following model for longitudinal vehicle movement and a rule based algorithm for lateral movements. VISSIM uses two different models for defining the driving behavior: Wiedemann 99 model and Wiedemann 74 model (Figure 10) (Fan, Wang, Liu, & Yu, 2013).

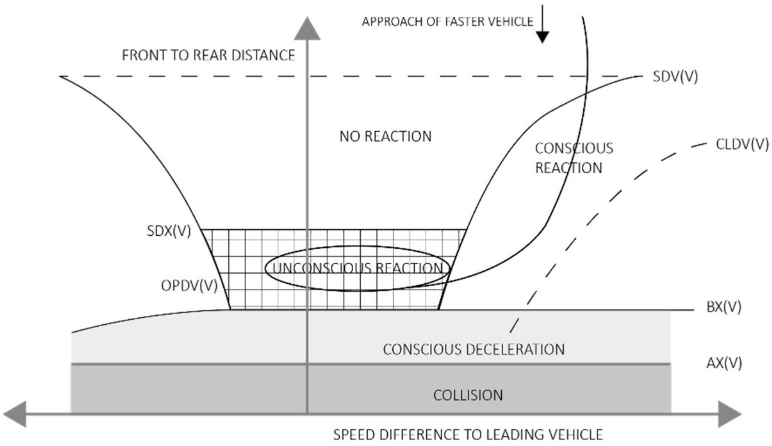


Figure 10: Psycho-physical car-following model by Wiedemann. Figure adapted from (Fellendorf & Vortisch, 2010)

The basic idea of the Wiedemann models is the assumption that a driver can have four driving modes (Papageorgiou, 2006):

- Free driving mode;
- Approaching mode;
- Following mode;
- Danger or brake mode.

The Wiedemann model uses a stochastic probability function to create a heterogeneous traffic streams and driving behavior can be simulated (Higgs, Abbas, & Medina, 2011). Traffic data that is collected by detector loops can be used in this type of simulation model because it represent the capacity on the road and the data is collected of individual drivers. The measures of performance are generated during the simulation, kept storage and files at the end of each simulation (Barcelo J. , 2010). The driver behavior model can be described with the Michon model (Figure 11) (Michon, 1985). This model will help to understand which traffic characteristics are important when specific set of rules of the platoons need to be defined.

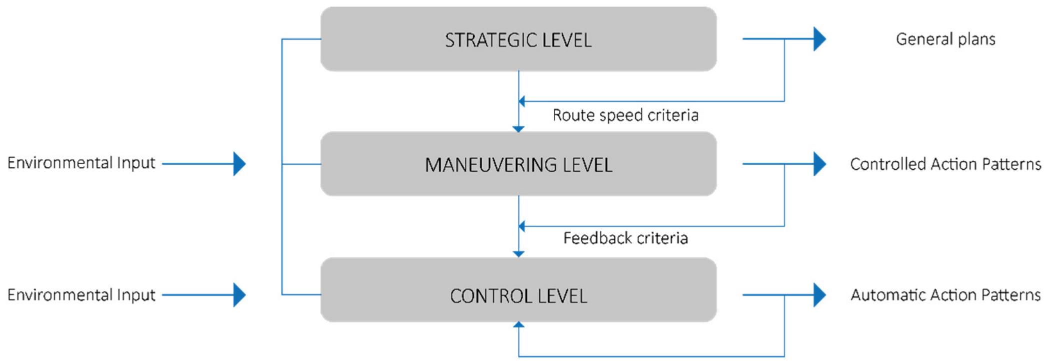


Figure 11: Michon model, the hierarchical structure of the road user task. Figure based and adapted from (Michon, 1985)

The driving behavior is divided in three levels: strategical (planning), tactical (maneuvering), and operational (control). The maneuvering level consists of the decisions that drivers make during travelling. This consists of obstacle avoidance, gap acceptance, turning and overtaking. The obstacle avoidance and the gap acceptance of other road users are a few core elements were truck platooning can have an effect on. A high penetration level of truck platooning can create obstacles and decrease the traffic safety. Therefore, road adjustments or strategies can be implemented to decrease the impact of truck platooning on a maneuvering level. The control level consists of the constraints of the road network like speed limits and inter vehicle distance (Michon, 1985).

3.4 MICROSCOPIC MODELING AND TRAFFIC SAFETY

Microscopic modelling can give an insight on the outcome of certain traffic strategies. Traffic management is influenced by many factors and trends. To analyze the impact of truck platooning on the driving behavior on Dutch road infrastructure the traffic flow, efficiency and safety can be analyzed. Traffic flow and efficiency can be evaluated in the microscopic simulation model itself by queuing, travel time, acceleration and deceleration graphs. The incorporation of traffic safety in microscopic simulation models is still in development and an ongoing process. Numerous of researches tested the traffic safety according to the following equation 3.1 (Young, Sobhani, & Lenné, 2014):

$$\textit{Expected number of crashes} = (\textit{number of conflicts}(c)) \times (\textit{crash-to-conflict ratio } (\pi)) \qquad (3.1)$$

Various studies have been carried out to analyze and develop a computer simulation that contribute to testing surrogate traffic safety. According to Dijkstra (2013), a leading vision in safety traffic planning and research is sustainable safety. Sustainable safety can be formulated as followed: *for each road category, road users know which behavior is required and what they may expect from other road users* (Dijkstra, 2013). In this research the traffic safety assessment was carried out by analyzing the safety level of a route on the basis of its characteristics that were assumed to be related to safety. With this method it is possible to evaluate a road network from a safety perspective. The safety assessment was carried out with Paramics and the safety was tested with the evaluation of the relation between crashes and conflicts.

Goh et al. (2013) developed a simulation modelling approach to test understand the safety effect of implementing a bus lane on a road corridor. Specific safety performance indicators, (1) Time-to-collision and (2) Deceleration rate to avoid a crash, were used to measure the safety performance. Results showed that bus lanes reduce conflict areas (Goh, Currie, Sarvi, & Logan, 2013). The safety benefits were depended on the creation and adjustments in the network. According to Fan et al.

(2012), safety assessments are challenging to validate. One of the concerns is that the output of the microscopic simulation files cannot reflect the difficult driving behavior in the real world. Thus, a safety assessment can be executed over the output of microscopic model but the results need to be interpreted carefully. The results on safety can therefore be biased and not completely reliable. These results will give an indication of the traffic safety in road networks, but are not an answer.

3.5 CALIBRATION AND VALIDATION OF TRAFFIC SIMULATION MODELS

Simulating techniques can be seen as a sampling experiment (Barcelo J. , 2010). The sampling experiment can be considered as observational and from the samples the variables of interest are collected. With these samples certain conclusions of the system behavior can be made. The reliability on the decision making process depends on the ability to produce a simulation model that represents the system's behavior as close as possible. This can be achieved through validation of the model. Validation is an iterative process that calibrates the model parameters, compares the model to the actual system behavior, and uses the discrepancies between the two (Barcelo J. , 2010). The model then can be improved until it is accurate and acceptable. With validation it can be determined if the simulation model is an accurate representation of the system. Within microscopic modeling calibration and validation is still challenging. Microscopic modeling has a high level of uncertainty because of the large number of parameters.

According to Barceló (2010) to validate a model, first a calibration of the model needs to be done. Calibration can be defined as the process of obtaining values from field data in a particular setting. With calibration the values of the parameters are determined and with these parameters a valid model can be developed. The data that is used as input for simulation models can be classified into two groups: directly observable data and not directly observable data (Barcelo J. , 2010). Observed data are the measurements of traffic variables (flows, speeds, occupancies). Data that is not directly observable are origin-destination matrices.

3.6 CONCERNS

VISSIM allows it users to specifically define each parameters which is important to construct a network that represent real world conditions. However, microscopic simulation has still some downside and according to previous paragraphs two important issues can be defined:

- *Calibration and validation is hard*: To fully understand the impact of truck platooning on the traffic management on the Dutch infrastructure the simulation model should be calibrated and validated with field data (Barcelo J. , 2010). Traffic data of truck platooning on the Dutch infrastructure is not available. Additionally, extensive traffic data should be collected to validate and calibrate the simulation model to accurately represent the traffic characteristics on the Dutch infrastructure.
- *Unrealistic driving behavior*: The driving behavior of vehicles is subjected to specific algorithms and car-following model (Appendix B2. Table B 2). Driving behavior is influenced by many factors and simulation tools have its limits to represent all those facets.

3.7 CONCLUSION

The impact of truck platooning can be simulated with the microscopic simulation software VISSIM. To analyze the impact of truck platoons on the A15 corridor certain steps need to be taken get specific output (Figure 12). The driving behavior and the intensity of trucks on the road on the A15 corridor has specific characteristics. Microscopic simulation does not represent the full reality of driving behavior on roads. With the adjustment of specific set of rules for the driving parameters the driving behavior can be simulated. Before the microscopic simulation model can be set up a data analysis needs to be executed. With the outcome of the data analysis, various traffic scenarios can be constructed and the intensity of trucks and other vehicles can be defined which need to be simulated. To verify if the parameters that are used as input are correct in the simulation model first various simulation tests needs to be executed.

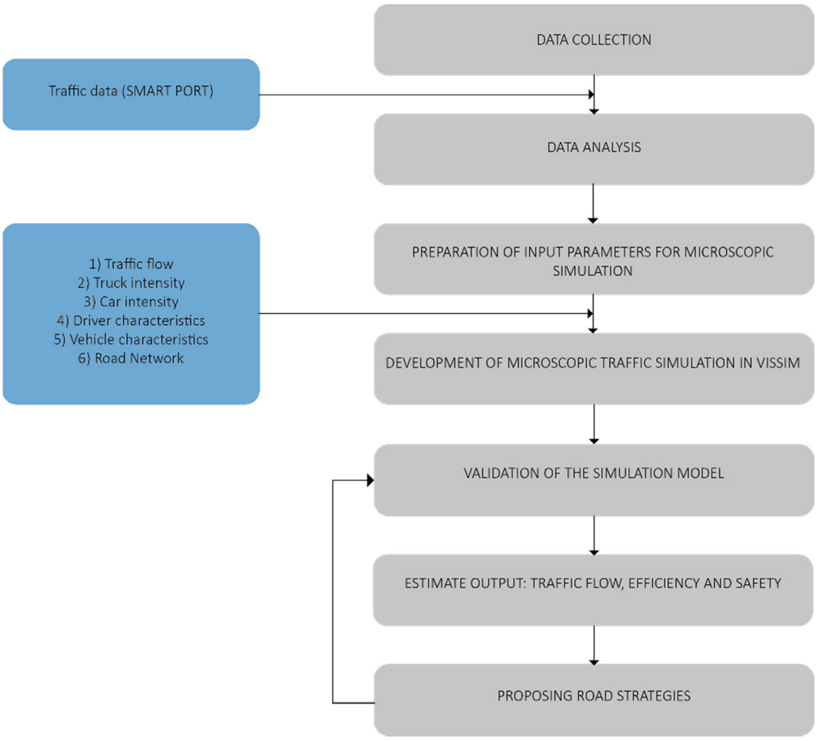


Figure 12: Simulation model methodology

3.8 DISCUSSION

Traffic simulation models are used to understand the traffic management and to analyze the results of implemented road strategies. Simulation of traffic can be done on various levels. With the microscopic model VISSIM, driving behavior and the interaction between vehicles can be better understood and analyzed. VISSIM is a software simulation model which is suitable to simulate truck platoons on the A15 corridor and to analyze the impact of this type of vehicle on the traffic management and the interaction with other road users. However, microscopic simulation models do not represent the full reality of the traffic system and therefore the outcomes are biased. When specific road strategies are proposed this should be taken into account.

CHAPTER 4

THE PORT OF ROTTERDAM AND A DESCRIPTIVE ANALYSIS OF TRAFFIC DATA

Traffic data can give an insight on the driving behavior of different types of vehicles. The traffic dataset of the A15 is analyzed on various groups on the parameters: velocity and intensity. A descriptive analysis is executed to define the mean and standard deviation of the velocity and intensity of two vehicle categories: cars and trucks. With the outcomes of the descriptive analysis, three scenarios can be defined where the microscopic simulations will be based on.

This chapter describes the characteristics of the A15 corridor and the execution of the descriptive analysis. The characteristics and case areas are described in section 4.1. Section 4.2, an elaboration is given on the traffic data of the A15. The data preparation and the assumptions that are made are discussed in section 4.3. Section 4.4 describes the descriptive analysis. A significant test is described in section 4.5. Finally, conclusions are formulated which are used for the microscopic simulations.

4.1 INTRODUCTION: THE PORT OF ROTTERDAM AREA

There is an increasing pressure on port activities, due to the inconvenience of transportation and industry near residential areas located near the port. The Port of Rotterdam draught a Port vision for the year 2030 . This vision indicates the ambition for the future of the port of Rotterdam. The focus areas of this vision are: accessibility, safety, livability and environment (Port of Rotterdam, 2015).

There is a modal shift towards inland transportation but road transportation is still indispensable in a multimodal transport planning. Short distances in the port area and to another end point are faster by trucks (Port of Rotterdam, 2016). The environmental footprint must be reduced by increasing the efficiency of the supply chain, decreasing downtime, increasing the load factor and reliability. To decrease this environmental footprint in 2030, 35% of the containers will be transported by road (Port of Rotterdam, 2015). Truck platooning is a solution to decrease the environmental footprint, fuel consumption and to increase road efficiency and support multimodal transportation system.

4.1.2 CHARACTERISTICS OF THE A15 CORRIDOR

The A15 is the main ITS corridor from the port area to inland end points (Figure 13). 80% of the trucks stays in a radius of 50 kilometers from the port of Rotterdam and eventually the trucks will ride up to Venlo (Jak, 2016). The A15 is partially a six lane highway and every minute, 12 trucks are registered at the A15 Botlecktunnel (Janssen, Zwijnenberg, Blankers, & Kruijf, 2016).

The A15 has two different traffic configurations. From measurement post 25.0 until 36.0 the A15 at the port area is a 2x2 lane highway (case area 2)(Figure 14). From measurement posts 36.0 until 72.3 has a 2x3 lane configuration (case area 1). Case area 2 lies near a vulnerable area and developments near this area are not desired. Additionally, the road has a relatively poor visibility for road users due to the curves of the A15.

Figure 13: Impression of the A15 corridor

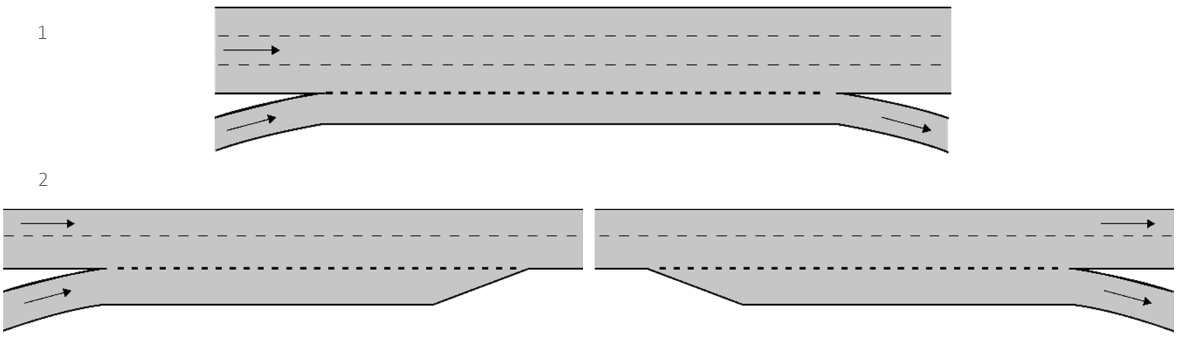


Figure 14: Case area 1 (weaving) and case area 2 (merging and diverging) of the A15

4.2 GENERAL INFORMATION OF THE TRAFFIC DATA

The traffic data from the A15 is obtained from Smart Port. Smart Port is a knowledge institution of the Port of Rotterdam. The traffic data is obtained by detector loops in the road infrastructure of the A15. Over a certain distance near a measurement post these detector loops are situated. The dataset contains the data of the velocity and intensity of various vehicles of the left and right carriageway of the entire A15. The dataset contains the data of the period 1st of January until the 31st of December of the year 2015 (365 days). The velocity and intensity of the traffic are registered per minute from 00:00 until 23:59.

4.3 DATA PREPARATION

To use the output of the data in a microscopic simulation the data first needs to be prepared. The data that is obtained by SmartPort is:

- Local mean speed, *'puntsnelheid'*: The average speed of all vehicles which pass through a cross-section in a given time period. Congestion can be determined on a road with the local mean speed. The local mean speed is expressed as kilometer per hour [Km/h].
- Traffic volume, *'Verkeersintensiteit'*: The amount of vehicles within a certain area at a certain time. With this parameter the amount of vehicles driving on the A15 can be simulated. The traffic intensity is expressed vehicle per hour [Veh/h].
- Vehicle category: The vehicles are divided by length into specific categories (Appendix A1)

Table 2: Vehicle category detected at the A15 corridor

Category	Vehicle length [meters]
1	< 5.6
2	5.6 < x < 12.2
3	> 12.2

There is an extensive amount of data available and therefore certain assumptions/statements need to be made in order to perform a descriptive analysis.

Left and Right carriageway

The intensity and velocity of the three vehicles categories are registered for the right and left carriageway (Figure 15). The data of the measurement post near the port area of the right carriageway are incomplete. The dataset contains 4 months of usable data of the year 2015. The amount of usable data is too limited because 33% of the data of the year 2015 can be used for the analysis of the right carriageway. Therefore, the data of the left carriageway is used in the descriptive analysis. The output of the analysis of the left carriageway is used as input for the microscopic simulation for the left and right carriageway. Hence, the simulations will not represent the reality of the traffic characteristics of the A15 completely. This will have an effect on the results and should be taken into account when further recommendation are written.

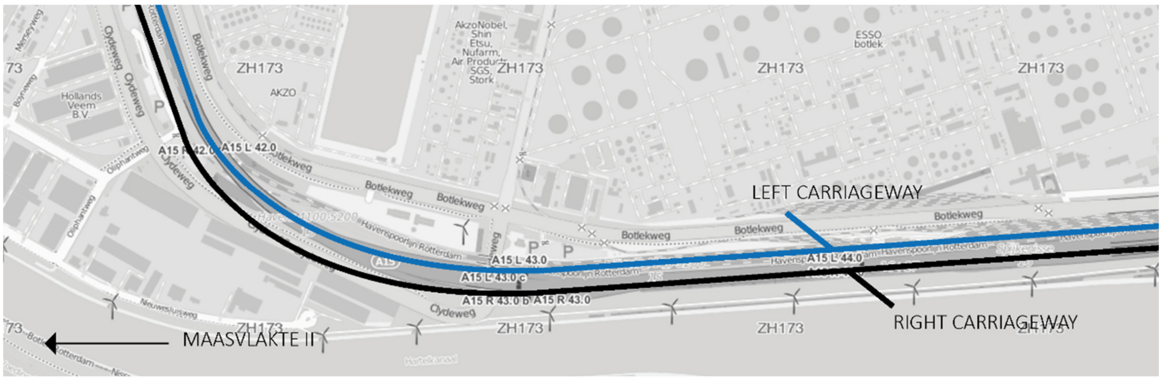


Figure 15: Left and right carriageway

Measurement posts

The data of the measurement post 47.365 of the left carriageway is selected and used in the descriptive analysis. The measurement post is situated near the *Botlecktunnel* (2x3 lane configuration).

Vehicle categories

Three vehicle categories are registered: Cat01, Cat02, Cat03. Vehicle category 2 has no distinct type of vehicle which can be assigned to this category (Appendix A1). Cars can be assigned to vehicle category 1, trucks can be assigned to vehicle category 3. Hence, vehicle category 1 and vehicle category 3 are taken into account for the analysis.

Handling of the data

The mean and the standard deviation are two parameters which can be analyzed correctly. The minimum and maximum values are not representative because the maximum and minimum can be an outliers.

Incomplete data and outliers

The dataset contains the data of the velocity and intensity of every minute of every day in the year 2015. However, in some months the data is not registered correctly. These months are September (12-9-2015 / 30-9-2015), October (1-10-2015 / 31-10-2015), November (1-11-2015 / 30-11-2015) and December (1-12-2015 / 31-12-2015). Within these months, only the values 0 and 144 occur in the dataset. These months are excluded from the analysis at the left carriageway. The missing values of the period autumn cannot be used in a descriptive analysis. However, 11 days are usable and are combined with the data of spring. The combined data of spring and autumn will be defined as remaining seasons.

The velocity is a dependent variable of the traffic intensity. If the intensity is not detected than the value 0 will be registered for the parameter intensity and velocity. However, the value 0 at the parameter velocity is not representative. The velocity of 0 km/h is not physically reached by any vehicle category at that moment. Hence, the value 0 at parameter velocity is defined as '-' and at the parameter intensity the value 0 is used.

Data categories

Traffic flows can be influenced by numerous of aspects. To understand the traffic flow at different times, certain groups can be defined. According to the literature study in Chapter 2, driving behavior is influenced by weather conditions, ratio trucks - cars, fatigue, stress. Therefore, the following groups can be defined to analyze what the velocity and intensity is and if specific variables within each group can be an influence on the traffic characteristics.

1)	Seasons	Winter (1-1-2015 / 28-2-2015), Remaining seasons (1-3-2015 / 31-5-2015 & 1-9-2015 / 11-9-2015), Summer (1-6-2015 / 30-8-2015)
2)	Holidays / *Non-Holidays*	1-1-2015, 3-4-2015, 5-4-2015, 27-4-2015, 5-5-2015 6-5-2015, 14-5-2015, 24-5-2015, 25-5-2015, 25-12-2015, 26-12-2015, Summer holiday central Netherlands: 27-7-2015 / 14-8-2015
3)	Weekdays / *Weekends*	Monday - Friday, *Saturday - Sunday*
4)	Peak hours / *Off peak hours*	06:30 - 09:30, 15:30 - 19:00, *00:00 - 06:29, 09:31 - 15:29, 19:01 - 23:59*

The division of these groups is based on the conditions that influence the traffic flow management on Dutch road infrastructure. The weather conditions vary within seasons in the Netherlands and this can have an impact on the traffic flow. The Netherlands has a high traffic intensity. This is because of the fact the Netherlands has a high population density and a high intensity of freight traffic (Centraal Bureau voor Statistiek, 2016). 78% of the total traffic on the Dutch road infrastructure are cars and 6% is freight transportation. The differentiation between holidays/non-holidays and weekdays/weekend is defined because the intensity of vehicles might be influenced by these days. Commuting takes place mostly during the week and at non-holidays. The A15 is the only road to the port area and commuting can have an influence on the overall traffic flow. The data of the holidays that are taken place at weekdays are considered as weekends (Appendix A2). These holidays are combined with the data of the weekends and are taken into the analysis of the subgroup weekend. Group 4, peak and off peak hours, is defined according to the guidelines of the Royal Dutch Touring Club ANWB (ANWB, 2016). According to the ANWB, most commuting takes place at a certain time of the day.

4.4 DESCRIPTIVE ANALYSIS

The descriptive analysis provides an insight in defining the mean velocity and intensity of the two vehicle categories. The analysis is conducted according to the assumptions stated in the previous paragraph. The descriptive analysis is executed with the program SPSS. The mean and standard deviation of the velocity and intensity of vehicle category 1 and 3 are calculated of every defined group. An indication is made of the mean, standard deviation and variance of the velocity and intensity of the year of 2015. Table 3 gives an overview of the results. It can be stated that the velocity of the A15 near the port area is lower than the maximum speed that is allowed (100 km/h). The outcomes showed that the intensity of the two vehicle categories is high.

Table 3: Descriptive of the year 2015 on the velocity and intensity of the vehicle category 1 and 3

	Mean Velocity [Km/h]		Mean Intensity [Veh/h]		Std. Deviation Velocity		Std. Deviation Intensity		Variance Velocity		Variance intensity	
	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3
Year 2015	**93,39**	**79,28**	1414,46	231,99	16,573	13,248	1110,920	269,247	274,655	175,502	1,23*10^6	7,25*10^4

The variance of the two parameters is relatively high which means that the measure of distribution of the values is high. Therefore, the various groups need to be analyzed to decide which specific type of data of which group can be used as input for the microscopic simulation.

Group 1: Seasons

The parameters mean, standard deviation and variance of the velocity and intensity of the various seasons can be calculated (Appendix A3.1). Table 4 gives an overview of the outcomes of winter, 'spring', summer. During winter the intensity and velocity of vehicle category 1 is significant higher than in the other seasons. This can be explained by the fact that people make less use of public transportation. This higher intensity has no effect of the overall velocity in the winter period. The velocity of vehicle category 1 is even higher during winter period than in other periods. An explanation is that the winter of 2015 can be classified as a relatively warm winter (KNMI, 2016).

Table 4: Mean of the velocity and intensity of vehicle category 1 and 3

Group 1	Mean Velocity [Km/h]		Mean Intensity [Veh/h]	
	Cat1*	Cat3	Cat1*	Cat3*
Winter	**95,47**	79,19**	**1694,61**	230,77
Remaining seasons	93,53	79,21**	1383,59	232,28
Summer	91,80	79,42**	1270,40	232,44

** These results are significant (Appendix A3.1.1)*

*** Winter & Remaining Season is significant, Remaining Seasons & Summer is significant*

These results do not taken any exceptions into account like, holidays, weekends or the peak and off peak hours. So these means on the parameters on velocity and intensity are biased.

Group 2: Holidays and Non-holidays

To get a clear impression on the driving behavior of the vehicles and the intensity on the A15 an analysis can be executed on the differences of velocity and intensity between holidays and non-holidays (Appendix A3.2). The variance on both parameters is quite high. This results is a relatively lower mean on the velocity and intensity (Appendix A3.2). In appendix A2, Table A2.1, an overview is given on the Dutch holidays that are determined by the Dutch government.

The intensity of both vehicle categories is significant lower during the holiday period. An explanation for this is that 75% of the time the car is used to commute (Centraal Bureau voor Statistiek, 2016). The low intensity of vehicle category 3 has an effect on the velocity of vehicle category 1 (Table 5). Stress of human drivers is associated with large trucks and has and the visibility of human drivers is influenced by the vehicle size. Trucks create a reduction in the vision of human drivers (Ferrari, 2009). Less truck on the road might influence the behavior of the human driver and therefore the human driver speeds up.

Table 5: Mean of the velocity and intensity during holidays and non-holidays

Group 2	Mean Velocity [km/h]		Mean Intensity [Veh/h]	
	Cat1	Cat3	Cat1*	Cat3*
Holidays	**96,11**	79,69	1151,21	**178,41**
Non-holidays	93,06	79,07	1447,95	272,005

** These results are significant*

Group 3: Weekdays and Weekends

The intensity of vehicle category 1 is higher during weekdays due to due to commuting. Dutch commuters travel an average of 12.000 kilometers per year (Centraal Bureau voor Statistiek, 2016). The intensity of vehicle category 3 is significant lower during the weekends. The incoming and out coming goods happen throughout the week. An explanation of the low intensity of vehicle category

3 during weekends can be that the distribution of goods to end points only happen during the weekdays because truck drivers of certain companies are only allowed to work during the weekdays.

Table 6: Mean velocity and intensity during weekdays and weekends

Group 3	Mean Velocity [km/h]		Mean Intensity [Veh/h]	
	Cat1	Cat3*	Cat1	Cat3*
Weekday	90,26	78,48	1523,38	323,44
Weekend	**100,29**	**83,79**	1176,31	**32,04**

** These results are significant*

Group 4: Peak hours and off peak hours

Previous paragraph showed that during the weekends the intensity of vehicle category 3 is significant lower than during the weekdays. Therefore, the peak and off peak hours are analyzed for the weekdays during different seasons (Table 7). The mean and standard deviations are calculated to show the differences per peak and off peak hour during a season (Appendix A3.4).

Between the three seasons the intensity of vehicle category 3 does not differ. The intensity of vehicle category 1 is higher during winter than during 'spring' and summer. The reason for this is that people tend to use the car more than public transportation due to weather circumstances (Centraal Bureau voor Statistiek, 2016). The intensity of vehicle category 1 and 3 is often equal during both peak hours. The reason for this is that during peak hours passenger vehicles mostly travel alone, 88% in the morning peak hour and 80% in the evening peak hour (Centraal Bureau voor Statistiek, 2016). The intensity during off peak hour (09:31 - 15:29) is higher than during the peak hours. The Port of Rotterdam encourages employees and trucks to ride after peak hours rather than during peak hours. The intensity of vehicle 3 is at its highest during this time of the day. The Dutch government and the ANWB also encourage this for other car drivers. The intensity of vehicle category 1 during the off peak hour, 19:01 - 23:59, is still quite high. A reason for this can be that employees start driving after peak hours.

Table 7: Mean velocity and intensity during peak and off peak hours within different seasons

Group 4	Mean velocity [Km/h] Peak hours 06:30 - 09:30		Mean intensity [Veh/h] Peak hours 06:30 - 09:30		Mean velocity [Km/h] Peak hours 15:30 - 19:00		Mean intensity [Veh/h] Peak hours 15:30 - 19:00		Mean velocity [Km/h] Off peak hours 09:31 - 15:29		Mean intensity [Veh/h] Off peak hours 09:31 - 15:29	
	Cat1	Cat3	Cat1	Cat3	Cat1*	Cat3*	Cat1	Cat3*	Cat1	Cat3	Cat1	Cat3
Winter	83,54	74,81	**3337,67**	440,77	71,80	64,42	**3465,32**	413,98	92,96	82,22	2168,50	**631,46**
Remaining seasons	81,86	73,71	2458,18	462,34	71,81	66,04	2497,87	431,82	91,64	82,19	1617,41	**629,38**
Summer	85,70	76,87	2101,95	445,30	80,57	73,14	2380,68	428,27	89,35	80,96	1553,65	**597,86**
	Mean velocity [Km/h] Off Peak hours 19:01 - 00:00		Mean intensity [Veh/h] Off Peak hours 19:01 - 23:59		Mean velocity [Km/h] Off Peak hours 00:00 - 06:29		Mean intensity [Veh/h] Off Peak hours 00:00 - 06:29					
	Cat1	Cat3	Cat1*	Cat3*	Cat1	Cat3	Cat1*	Cat3*				
Winter	102,18	84,21	1279,51	**100,33**	100,17	82,76	618,92	**106,49**				
'Spring'	98,15	83,45	1176,99	**112,00**	97,02	82,10	512,63	**108,23**				
Summer	94,35	81,33	1091,39	**101,32**	92,73	80,07	460,03	**97,07**				

Peak an off peak hours are based on the data of the ANWB (ANWB, 2016)
** These results are significant*

4.5 SIGNIFICANCE TEST: CHI-SQUARE TEST

To use the output of the descriptive analysis, first an significance test needs to be executed. The dataset is divided into two clear vehicle categories. The Chi-square test can be used to analyze the differences between two variables is significant or not. The Chi-square shows you if the data is significant but does not show how strong the significance is. The Chi-square goodness-of-fit test is can be used to determine whether the distribution of cases (e.g. vehicle categories) follows a known or hypothesized (Laerd Statistics, 2016). The Chi-square test can be formulated by equation 4.1 (Howell, 2016):

$$\chi^2 = \Sigma \frac{(0-E)^2}{E} \qquad (4.1)$$

x^2	=	Chi-Square
0	=	Observed frequencies
E	=	Expected frequencies

The Chi-square value needs to be below 0,05, thus $\mathrm{P} < 0{,}05$. How bigger the Chi-square the bigger the difference between groups. The Chi-square test can be used if two conditions are met:

- The assumption must not exceed above 20% and the expected count is less than 5
- All expected outcomes are larger than 0

If certain conditions are not met, the likelihood ratio chi-square test can be used. The likelihood ratio Chi-square builds on the likelihood of the data under the null hypothesis relative to the maximum likelihood. The likelihood ratio chi-square is defined as (Howell, 2016):

$$G^2 = 2\,\Sigma \left[Oij \log \frac{Oij}{Eij}\right] \qquad (4.2)$$

0	=	Observed frequencies
E	=	Expected frequencies

An advantage of the likelihood ratio Chi-square is that G^2 for a large dimensional table can be decomposed into smaller components (McHugh, 2013). The Chi-square test shows you if the data is significant but does not show how strong the significance is. Therefore, a Cramer's V test is also executed. With this test the statistical strength of the correlations are measured. The larger the outcome of a Cramer's V test, the stronger the relationship is between variables (Anderson, 1989). Cramer's V test can be formulated by the equation 4.3 (McHugh, 2013):

$$\sqrt{\frac{x^2}{n(k-1)}} \qquad (4.3)$$

n	=	Total observations
k	=	Number of rows or columns

The significance test is separately executed over the 4 groups within the two vehicle categories: vehicle category 1 and vehicle category 3.

4.5.1 SIGNIFICANCE TEST

The difference within a certain category can be tested with the Chi-square test. The outcomes on the parameters velocity and intensity in every group are partially significant. However, if there is a significance, the significance is not strong and can be defined as weak (Appendix A3.1.1.3). Overall the outcomes on the intensity of both vehicle categories are significant in the groups 1 and 2, and the velocity and intensity of vehicle category in group 3. An explanation for the partial significance within the 4 groups can be explained by how the data of the intensity and velocity is registered by the detector loops. The intensity of both vehicle categories can be registered accurately. The registration of the velocity is more complex. The detector loops register in 1 minute multiple vehicles with their own velocity. This velocity is combined and register as one mean velocity.

Within the 4 groups the intensity in most cases is significant. An explanation might be that the intensity can be registered accurately with the same circumstances for both vehicle categories. However, in group 3 the velocity and intensity of vehicle category 3 are significant. The distribution of goods happens mostly during the week and therefore there is a significant difference between the intensity during the weekdays and weekends. The results in group 4 are mostly not significant. An explanation of this can be that in this analysis the data is divided in too many categories.

A small amount of the outcomes of the descriptive analysis is significant. A possible explanation of the partial significance is that not all the data was available. The dataset contained error values and these needed to be eliminated. A partial significance of the outcomes of the descriptive analysis will have an influence on the reliability of the microscopic simulation. To validate the microscopic simulation the data needs to represent the real situation as good as possible and this is not completely possible with partial significant data. This needs to be taken into account when recommendations are presented.

4.6 CONCLUSION

The output of the descriptive analysis is going to be used as input for the microscopic simulation. The Chi-square test showed that not all the outcomes of the descriptive analysis are significant. The results will be biased and not completely reliable. This should be mentioned when recommendations are suggested. The following statements can be made where the microscopic simulation will be based on:

- The peak hours (06:30 - 09:30 ; 15:30 - 19:00) and off peak hour (09:31 - 15:29) are the basis for the microscopic simulation. These times of the day represent 3 scenarios with their own traffic characteristics (Figure 16);
- The traffic data of the peak and off peak hours during the weekdays are used. These represent in most detail the traffic characteristics of the A15;
- The outcomes of the seasons of the peak hours and the off peak hour are combined, because these results are not significant and can be considered as one value;
- The standard deviation is used to set a minimum and a maximum for the intensity and the velocity of the two vehicle categories (Appendix A3.4).

The minimum, mean and maximum will be used as tipping points in the simulation (Figure 16 & Figure 17) (Appendix A5). The minimum, mean and maximum represent the penetration level of the truck platoons on the traffic flow management. These tipping points will indicate if certain road infrastructure adjustments need to be made in order to optimize the traffic flow management and increase safety for other road users.

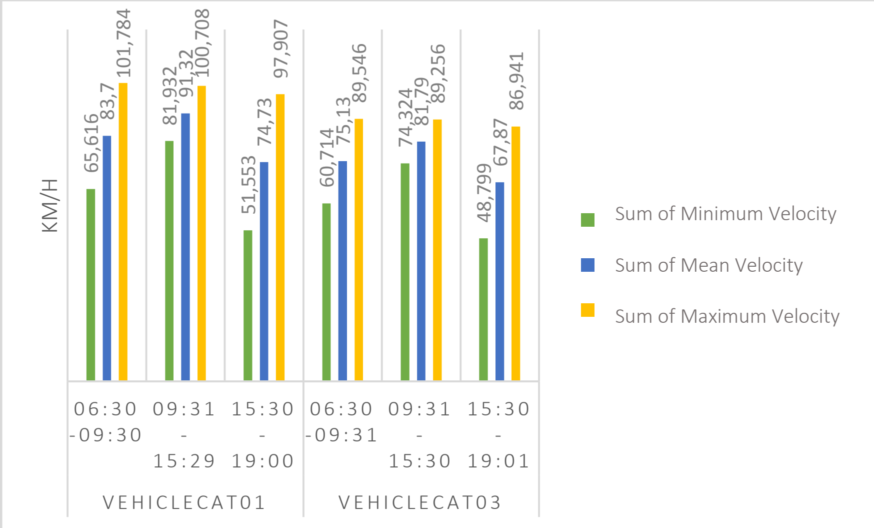


Figure 16: Three scenarios of the velocity of vehicle category 1 and 3

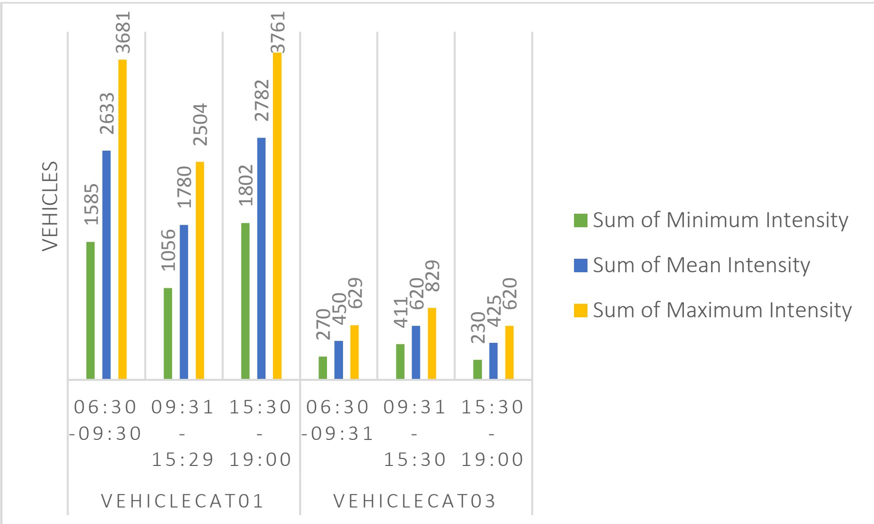


Figure 17: Three scenarios of the intensity of vehicle category 1 and 3

4.7 DISCUSSION

The execution of the Chi-square test on the various groups showed that the outcomes are partial significant. However, not one of the outcomes of a group is significant and can be the basis for the microscopic simulation. The intensity during the different seasons in group 1 are significant and can be used in the simulation. Trucks drive mostly during the weekdays and not in the weekends. This is not taken into account in the intensities of group 1. Thus, the overall intensities within the seasons (group 1) does not represent the characteristics of the A15 corridor. Because the outcomes of the different seasons within every peak hour and off peak hour is not significant the results cannot be generalized. Every seasons should be simulated separately with its own characteristics if these outcomes are the basis for the simulation.

The characteristics of the A15 are represented the most in the analysis of the peak hours and off peak hours. The results are however not significant. If these outcomes are used as the basis of the microscopic simulation the results can be biased. The results of the simulation do not represent the traffic situation of the A15 in reality. If these outcomes are used in the simulation this should be taken into account when recommendations are suggested.

CHAPTER 5

SIMULATION EXPERIMENTS: THE INFLUENCE OF TRUCK PLATOONING ON TRAFFIC FLOW, EFFICIENCY AND SAFETY

Simulations can play an important role in understanding the impact and effectiveness of certain strategies and new mobility technologies. The impact on the traffic flow, driving behavior of other road users is not a straightforward relation and is still unclear. With simulations first steps can be taken to understand the impact of large scale truck platooning on the A15 corridor.

In section 5.2, the model development of VISSIM is discussed. This section will discuss the system architecture of VISSIM, the parameters which should be included and how the traffic network is built in the simulation model. The verification of specific parameters that are used in the simulation models is discussed in section 5.3. The hypothesis and results are explained in section 5.4. The results and outcomes are formulated in section 5.5. The assumption which are made and that can be of influence on the outcomes are addressed in section 5.6.

5.1 INTRODUCTION

The impact of large scale platooning on traffic management is still unclear. The derived traffic data is used as input for the experiments executed in VISSIM. A visualization of a constructed network is given in Figure 18.

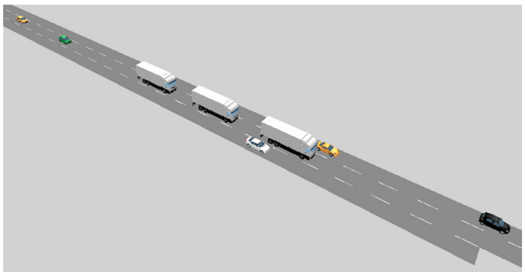


Figure 18: Snapshot of the infrastructure network in VISSIM of case area 2

5.2 MODEL DEVELOPMENT: VISSIM

The impact of large scale platooning is tested on complex traffic locations on the A15 corridor. The network constructed in VISSIM is based on these traffic locations. First the car-following behavior where VISSIM is based on is discussed in section 5.2.1. To set up the experiments in a VISSIM environment specific parameters should be defined. This is discussed in section 5.2.2. How the network is constructed with the specific parameters is discussed in section 5.2.3.

5.2.1 CAR-FOLLOWING BEHAVIOR IN VISSIM

Car-following behavior in VISSIM is described by the Wiedeman 74 and Wiedemann 99 model. The Wiedemann 99 model is suitable for freeway traffic behavior (Gao, 2008). The Wiedemann model can be defined with the following mathematical formula (Gao, 2008; ptv, 2011):

$$u_n(t+\Delta t) = \min\left\{ \begin{matrix} u_n(t)+3.6\cdot\left\{CC8+\frac{CC8-CC9}{80}U_n(t)\right\}\Delta t \\ 3.6\cdot\frac{s_n(t)-CC0-L_{n-1}}{U_n(t)}, u_f \end{matrix} \right\} \quad (5.1)$$

u_n = Speed vehicle [km/h]
Δt = Difference in time [s]
l_n = Effective length of vehicle [m]
s_n = Spacing between vehicle at a certain time to the preceding vehicle [km/h]
u_f = Space-mean traffic stream free flow speed [km/h]
$CC8$ = Maximum desired vehicle acceleration at a speed 0 km/h
$CC9$ = Maximum desired vehicle acceleration at a speed of 80 km/h
$CC0$ = Standstill distance (average desired standstill distance between two vehicles)

The default value for CC8 is 3.50 m/s^2 and for CC9 is 1.50 m/s^2. These values are kept as default values because these are intertwined with the car-following behavior where VISSIM is based on (ptv, 2011; Gao, 2008). The driving behavior of vehicles is set on *freeway* which corresponds to the above mentioned equation and to the traffic rules of Germany which are also applied in the Netherlands (ptv, 2011). The outermost right lane is defined as the slow lane and the outermost left lane is defined as the fast lane.

Driving parameters of the Wiedemann model are defined by CC0 up to CC9. The first four parameters describe the vehicle distance, the next three parameters describe the speed of the following vehicle and the last three parameters describe the acceleration in the process of following a vehicle. The parameters can be described as followed (Gao, 2008; ptv, 2011):

- *CC0* (Standstill distance): Desired distance between stopped vehicles, default value is 1.50 meters;
- *CC1* (headway time): desired time headway in seconds between the lead and following vehicle; default value was 2 seconds. However, in the Netherlands the headway time is smaller and is set at 0.9 seconds (SWOV Institute for road safety research, 2017);
- *CC2* (Following variation): Additional distance over safety distance that a vehicle requires and controls the longitudinal oscillations. Default value is set on 4 meters;
- *CC3* (Threshold for entering 'following'): Controls the start of the deceleration process before reaching the safety distance. Default value is set on -8 meter/second;
- *CC6* (Speed Dependency of oscillation): influence of distance on speed oscillations. Default value is 11.44;
- *CC7* (Oscillation Acceleration): Acceleration during the oscillation process, default value 0.25 m/s²;
- *CC9* (Acceleration at 80 km/h): Desired acceleration at 80 km/h. The default value is set on 1.50 m/s².

The default values are based on traffic data from German highways. The conditions on these highways can be considered as equal to the conditions at Dutch highways. Therefore, these values are kept as default values. Additionally, calibration and validation of each of these parameters is still difficult because in situ data can be hard to collect (Gao, 2008). If one of these parameters is adapted the following behavior of the simulation model can be unrealistic. One default value is adjusted and that is the headway time. Driving behavior in the Netherlands can be labeled as compulsory (Marczak, Daamen, & Buisson, 2013). A minimum of a 2 seconds headway time is advice on motorways where the traffic situation is complex. Drivers accept smaller gaps in the Netherlands and the headway time is shorter in the Netherlands compared to other countries. The headway time for cars is less than a second and for trucks the headway time is 1.3 seconds (SWOV Institute for road safety research, 2017). The headway time distance (CC1) in VISSIM is set on 0.9 seconds for freeways.

5.2.2 DEFINING PARAMETERS FOR INPUT

To set up the simulation in VISSIM, first a specific set of rules and parameters needs to be defined. The vehicles that move in the network are constrained by the overall rules of the traffic management layer of the A15. Human driven vehicles are already implemented in the software model (ptv, 2011).

Traffic scenarios as base simulation scenarios

Three scenarios are set up for the experiments. Within each scenario the intensity of trucks varies. These scenarios are assessed on traffic flow, efficiency and safety. An overview of the exact input variables of the three scenarios are given in Appendix B1, Table B 1. The scenarios are defined according to the results of the descriptive analysis described in section 4.6.

Scenario 1: *Peak hour (06:30 - 09:30)*	Minimum Intensity Trucks	-	Mean intensity cars
	Mean Intensity truck	-	Mean intensity Cars
	Maximum Intensity trucks	-	Mean intensity Cars
Scenario 2: *Off peak hour (09:31 - 15:29)*	Minimum Intensity Trucks	-	Mean intensity cars
	Mean Intensity truck	-	Mean intensity Cars
	Maximum Intensity trucks	-	Mean intensity Cars
Scenario 3: *Peak hour (15:30 - 19:00)*	Minimum Intensity Trucks	-	Mean intensity cars
	Mean Intensity truck	-	Mean intensity Cars
	Maximum Intensity trucks	-	Mean intensity Cars

Traffic characteristics A15

The vehicles of the A15 are subjected to specific network constraints. The maximum speed on the A15 corridor is 100 kilometers/hour. The width of the lanes are 3.50 meters according to the guidelines of the Dutch ministry of infrastructure and environment (Rijkswaterstaat, 2016). In the Netherlands, slower vehicles are assigned to the right lane and faster vehicles outermost left lane. In the experiments trucks and platoons are assigned to the right lane. Two vehicle types are simulated: cars (attribute 100) and trucks (attribute 200). Multiple vehicles (e.g. cars with trailers, smaller trucks) drive on the A15 corridor and therefore the results of what the impact is on platooning and the traffic management is biased. This should be taken into account when road traffic management strategies are proposed.

Driver characteristics

The network that are constructed in VISSIM are relative 'simple' network. Static routing is used to predefine the routing decisions of vehicles. According to the results of chapter 4, the velocity between trucks and cars differ. Therefore for each vehicle category a velocity range is defined. The limit of the velocity is not reached according to the traffic data represented in Figure 16, The maximum is 105 km/h. This allows vehicles to accelerate to merge or diverge and the velocity constraint is not a hard constraint which can influence the results of the experiments.

$$65.61 \text{ km/h} < v_{cars} < 105 \text{ km/h}$$

$$60.71 \text{ km/h} < v_{trucks/platoons} < 89.55 \text{ km/h}$$

Driving behavior

In this research driving behavior is defined as: *the movement of vehicles within a network that is subjected to the overall velocity, acceleration/ deceleration behavior of the traffic network and is influenced by the driving behavior of other vehicles within the network*. Driving behavior is influenced by engineering and human factors (Alian, Baker, & Wood, 2016). Human factors are not taken into account due to the fact that psychological state of drivers is hard to analyze.

Requirements truck platoons

The platoon in the simulation model consists of three trucks with an inter vehicle distance of 6.7 meters which corresponds to a total length of 69.75 meters. The weight of trucks within a platoon is homogeneous. The following characteristics of a truck platoon need to be strictly defined in the simulation model.

Characteristics platoon: The length of a truck is set on 18.75 meters and width at 2.55 meters according to the guidelines of the European union. Longer and heavier vehicle combination (LZV) are not included in the simulations due to the fact that first standard trucks are used to establish a platoon. There is no weight difference within the platoon and is considered as homogeneous entity. All the platoons are subordinate to the 'slow lane' rule which implies that all platoons will drive on the right side of the road.

Look back and ahead distance: The platoons are considered as SAE level 4 which indicates that there is no human intervention while driving. Numerous of literature articles define a specific look ahead and look back distance. Herein, there is no clear generalized assumption defined. The look ahead distance of the first vehicle in a platoon is assumed as 250 meters and the look back distance is 150 meters maximum (Gao, 2008).

Lane change behavior

Lane change behavior can be divided in compulsory lane changing or courtesy lane changing. Lane change behavior in VISSIM should be constructed correctly or else unrealistic lane change behavior will occur. The values for the look ahead distance near a diverging lane are set on 1200 meters. This value correspond to the time when driver on Dutch freeways are informed by signs that lane changing needs to be executed to follow the desired travel direction.

Lane change behavior of vehicles obey specific traffic rules according to the car-following behavior discussed in paragraph 5.2.1. Compulsory lane changing is not included in the simulation model. Nonetheless, the simulation model can allow vehicles to *cooperatively change lanes*. When vehicles want to merge onto the adjacent lane it is possible that vehicles partially cooperative change lane by courtesy or decelerate slightly to allow vehicles to merge. With this adjustment lane change behavior is more realistic.

5.2.2 SET UP OF THE TRAFFIC NETWORKS IN VISSIM

In previous paragraphs the parameters are defined that are used as a specific input for the VISSIM traffic networks. The traffic network that is constructed in VISSIM is based on the two traffic location at the A15 corridor discussed in section 4.1. Three network locations on the A15 corridor are defined: weaving, merging and diverging areas.

The measures of performance are generated during the simulation and are translated to output files in excel (Barcelo J. , 2010). The traffic network consists of links (blue) and connectors (purple) (Figure 19). With these elements a traffic network can be constructed. Figure 19 gives an overview of these connectors and links. The characteristics such as length, width of a traffic lane, if overtaking is allowed can be defined for each link and each connecters. Connectors are necessary to create merging and diverging areas (ptv, 2011). Data collection points can collect specific data of each vehicle type. Area measurements can also be analyzed by defining a begin point and end point (Figure 19) Table 8 gives an overview of the input variables of each traffic location constructed in VISSIM.

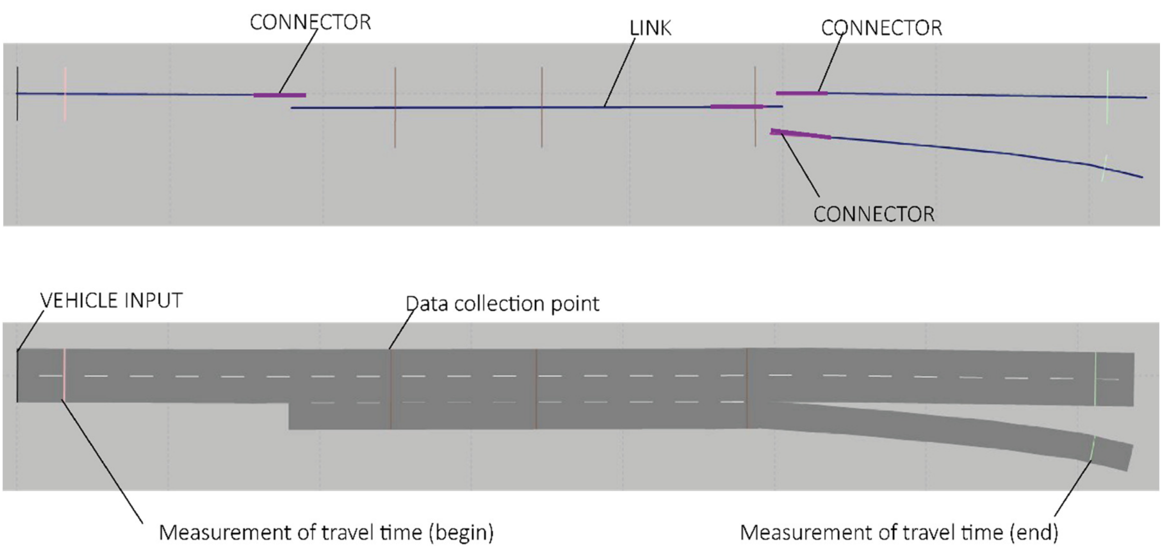


Figure 19: Constructing a traffic network in VISSIM. The figure above represents the network in wireframe with its links and connectors

Table 8: Variables that are important when constructing a traffic network, obtain specific results and start simulating

Variables	Value parameters	Explanation
Simulation speed	10 simulation sec/sec	Corresponds to a time laps factor. Indicates the simulation seconds per real-time second. With this set up simulations can run faster and no information gets lost or less accurate (ptv, 2011)
Number of runs	5 runs	Indicates the number of runs that are performed in a row. Multiple runs create a more accurate output and this is achieved with 5 runs (ptv, 2011).
Evaluation configuration	Queue counters; Stopped delay; vehicle travel time, vehicle record; vehicle network performance	Collected data of the simulation models is written in excel files. In the excel files the queue delay, vehicle travel time, stopped delay, acceleration/deceleration behavior is given per vehicle type and per data collection point. This data is collected by the data collection points and area measurements.
Routing decision	Static	Pre-defined routing decision to direct vehicles in a specific direction to obtain data about lane changes.
Size network	1800 meters	Traffic network are constructed not only with the traffic location itself but also an area upfront the traffic location where the vehicle stream could stabilize.
Driving behavior	Wiedemann 99: Freeway	Right lane - slow lane. Vehicles with a lower speed will drive at the outer most right lanes. Over taking is allowed.
Link & connectors		Attribute to build a network. Width, length and the number of lanes can be defined by this variable (blue lines).
Connector		Can connect other links (purple lines). Lane changes can be performed smoother in the network with connectors
Length merging lane	180 meter	
Length diverging lane	120 meter	
Length weaving area	1000 meter	
Vehicle input		Is defined according to the results discussed in Chapter 4, Figure 17. The ratio of trucks - cars is given in Appendix B 1 , Table B 1.

5.3 VERIFICATION OF PARAMETERS FOR THE SIMULATION MODEL

Microscopic simulation models have a high level of uncertainty and it is a challenge to validate and calibrate these type of models. According to Fan et al. (2012) the parameters which should be validated before simulations are executed are: lane changing, minimal gap acceptance, safety distance, standstill distance (CC0), headway time (CC1) and threshold for entering 'following' (CC3). According to Oud (2016) the validation of the parameter gap acceptance is still difficult. The gap acceptance in VISSIM is generated by an algorithm with specific boundary conditions. To validate the simulation output it needs to be compared with real traffic data. The obtained traffic data that is obtained by SmartPort cannot be used to validate specific parameters. Therefore, the parameters that are dependent on the descriptive analysis discussed in chapter 4 are verified with existing literature. To approximate the driving characteristics of the A15 corridor at least the following parameters should be implemented and verified with existing literature and data:

- Intensity;
- Velocity;
- Acceleration & deceleration.

To verify the input variables of the simulation model, 15 simulation runs are executed with different random seeds. The verification of the three defined parameters are explained by the results retrieved from case area 2.

Speed distribution

The mean velocity of trucks and cars is set at 83.7 and 75.13 kilometers/hour within the defined range. In the simulation model vehicles are stochastically assigned to a specific velocity within the velocity range. Most vehicles are assigned to the mean velocity (Appendix B3,Figure B 1 & Figure B 2). It is clear that the output of the simulation model corresponds to the output of the data set (Table 9).

Table 9: Velocity distribution of vehicle category 1 and 3 of the base simulation morning peak hour case area 2

Vehicle Category 1			Vehicle Category 3		
	Data	Simulation model		Data	Simulation model
Mean	83,7 km/h	83,4 km/h	**Mean**	75.13 km/h	77,3 km/h
Lower Limit	65,2 km/h	66,3 km/h	**Lower limit**	60.7 km/h	65,68 km/h
Upper Limit	101,8 km/h	100,1 km/h	**Upper limit**	89,6 km/h	101,9 km/h
Mean lower limit	-	69,8 km/h	**Mean lower limit**	-	67,4 km/h
Mean Upper limit	-	89,8 km/h	**Mean Upper limit**	-	78,9 km/h

The acceleration and deceleration is not registered by the detector loops and the retrieved results from the experiments need to be checked with available literature (Table 10) (Ministerie van Infrastructuur en Milieu, 2015).

Table 10: Acceleration and deceleration values
(Ministerie van Infrastructuur en Milieu, 2015)

Acceleration	Deceleration	Simulation results	
1.0 m/s²	-1.5 m/s² (normal), -2.5 m/s² (last moment)	0.17 m/s²	-0.25 m/s²

With the verification of these specific parameters, the characteristics of the A15 corridor can be approximated. Table 11 gives an overview of the values that are set for specific parameters in VISSIM.

Table 11: Driving parameters human passenger cars

CC0 (Standstill distance)	**1.50 m**
CC1 (headway time)	0.90 s
Safety reduction factor	0.10 s
Waiting time before diffusion	60 s
Accepted deceleration	- 2.50 m/s²
Look ahead distance	1200 m

5.4 EXPERIMENTS TRUCK PLATOONING IN BASE SCENARIOS

From the literature study in chapter 2, three hypothesis can be formulated. These three hypothesis can be answered by the experiments executed in the simulation model.

Hypothesis 1: Overall the traffic flow will increase due to truck platoons:
Platooning increases road capacity and with a short inter vehicle distance the fuel consumption is reduced (Alam, Besselink, Turri, Martensson, & Johansson, 2015; Trantow, Stieger, Hees, & Jescke, 2013). Hence, it can be stated that large scale platooning will increase the overall traffic flow. Vehicles are less influenced by trucks on the road and this might increase the overall velocity and travel time during peak hours.

Hypothesis 2: Lane changing within complex traffic situations can be affected by the short inter vehicle distance of a platoon and a vehicle delay can occur
According to paragraph 2.4.2, merging behavior is affected by the size and length of vehicles, gap acceptance. With a short inter vehicle distance queueing near weaving, merging and diverging lane occurs more frequently with large scale platooning because of the short inter vehicle distance and the length of a platoon.

Hypothesis 3: Traffic safety near merging, diverging and weaving areas will increase
Platooning can increase the traffic safety because the human error is decreased (Alkim, Vliet, Aarts, & Eckhardt, 2016). Near weaving, merging and diverging areas the amount of traffic conflict can increase due to the presence of trucks on the road (Li & Sun, 2017; Liu, Li, & Jia, 2014). Thus, with large scale platooning the human error is decreasing and the road capacity increases which is beneficial for the overall traffic safety.

The three hypothesis are tested for the two case areas stated in chapter 4. The hypothesis focusses on traffic flow, efficiency and safety. Table 12 gives the an overview of the definitions of the criteria and how these can be measured.

Table 12: Definition of the variables were the assessment of the experiments is based on

	Definition	Measured by
Traffic flow	Traffic has no fluctuations in acceleration and deceleration behavior and the vehicle travel time is not affected by road geometry and other vehicles	*Vehicle travel time; Acceleration/deceleration behavior; velocity*
Efficiency	Vehicles encounter no moving bottlenecks and no queueing on the road occurs.	*Queue delay*
Safety	Vehicles encounter no traffic conflicts and no unnecessary stops are executed to change lanes	*Stop delays*

An explanation of the standard figures of the experiments is given in Table 13. The three scenario (morning peak hour, daytime off peak hour and afternoon peak hour) that are defined in paragraph 5.2.1 are all compared with each other on these three criteria. With this comparison it can be analyzed if the time of the day is of influence on the impact of large scale truck platooning on traffic locations on the A15 corridor.

Table 13: Explanation of basic figures where the three criteria are assessed on

Traffic Situation	Criteria	Type of figure	Explanation
Weaving; Merging; Diverging	*Traffic flow*	*Travel time:* *x - as: Travel direction (e.g. A15 + merging, A15+ Diverging)* *y - as: Seconds*	*Platooning increases road capacity, which can decrease the amount of travel time within traffic location.*
		Velocity: *x-as: Traffic lanes of the traffic location (e.g. scen 1: lane 1)* *y-as: Kilometers/hour*	*The overall velocity can increase because platoons increase the road capacity and are assigned to the right lane*
		Acceleration/Deceleration: *x-as: Traffic lanes of the traffic location* *y-as: m/s²*	*Acceleration and deceleration behavior can indicate that there are fluctuations in the driving behavior of vehicles. The traffic flow can be affected negative or positive by these fluctuations.*
	Efficiency	*Queue delay:* *x-as: Traffic lanes of the location* *y-as: Seconds*	*Queue delay can indicate that a moving bottleneck is developing within the traffic location. Drivers are influenced by the size and length of vehicles when they want to perform a lane change (Ferrari, 2009)* *Queue delay is registered when v < 50 km/h. Within the traffic locations data collection points are set at the beginning of the location and at the end. The velocity is registered within this area if it is exceeding v > 50 km/h. If not, a queue delay is registered*
	*Safety**	*Stop delay:* *x-as: Travel direction (e.g. A15+ Merging, A15, A15 + Diverging)* *y-as: Seconds*	*The stop delay is registered within the traffic location if v = o km/h. Safety can be influenced by age, psychological state as well as various types of road users (Wegman, 2016)* *Testing safety in simulation models is still challenging because it is influenced by human and engineering factors (Alian, Baker, & Wood, 2016). The stop delay of vehicles gives an indication that vehicles have difficulties performing a lane change to the adjacent lane.*

** Safety is influence by various factors. In this research only the factors that are related to engineering are taken into account.*

5.4.1 IMPACT OF PLATOONING ON WEAVING AREAS

According to chapter 2, platooning increases the road capacity and this is beneficial for the overall traffic flow on the infrastructure (Alam, Besselink, Turri, Martensson, & Johansson, 2015). Platooning does have an influence on the travel time. With a minimum intensity of platoons on the road the travel time slightly reduces and the velocity increases on every traffic lane (Figure 21 & Figure 22). The velocity on lane 1 is low compared to lane 5 because lane 1 is the 'slower' lane and lane 5 is the 'fast' lane (Figure 20). Thus, it can be stated that platooning within a weaving area is enhancing the traffic flow compared to single trucks on the road.

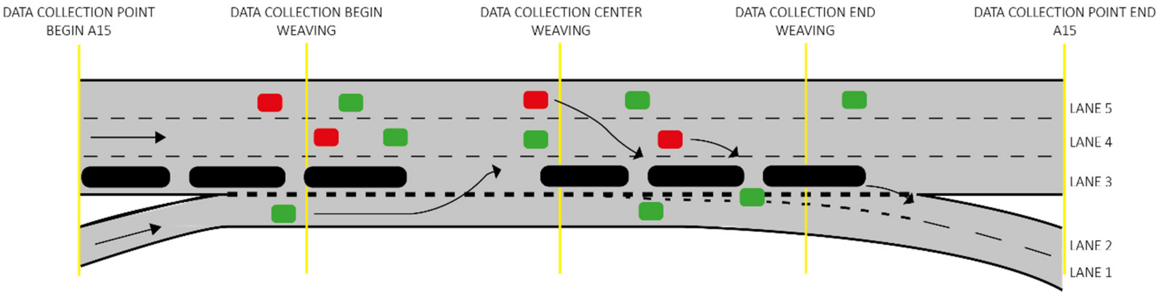


Figure 20: Weaving area on the A15 corridor with its data collection points

Platooning is beneficial for the overall traffic flow and the prediction is that lane changing can occur more frequently and faster within the weaving area. At the beginning and at the center of the weaving area the delay time is reduced by platooning (Appendix B4.1, Figure B 7). However, at the end of the weaving area queue delay increases on all 5 traffic lanes. At lane 5 ('fast lane') the queue delay is the highest (Figure 23). When lane changes need to be performed by vehicles the velocity is affected and a queue delay occurs. Vehicles need to perform 3 lane changes to merge onto the two deceleration lanes. Platoons on lane 3 can form a blockage and lane changing of other vehicles to this lane can be difficult. Additionally, at the beginning of the weaving section vehicles merge onto lane 3. Therefore, the velocity at the end of the weaving section is affected even on the outermost left lane (lane 5).

The queue delay of cars reduces when platoons drive on the road (Figure 23). Queueing within the weaving area is caused mostly by platoons (Figure 26 & Figure 27). Platoons are assigned to the right lane on the A15 corridor and have a lower speed compared to cars (lane 3). At the end of the weaving area vehicles are continuing their direction on the main corridor or change lanes to diverge. The queue delay of platoons on lane 3 and the low velocity can influence the lane changing behavior on lane 4 and 5 (Figure 26). Vehicles need to decelerate to merge into the adjacent lane and are influenced by the vehicle distance between two different platoons. Thus, vehicles lower their speed or even need to stop to perform a lane change. This reduces the overall efficiency of the weaving area.

Truck platooning can affect the driving behavior of other vehicles due to the length, short inter vehicle distance and the variation in speed (Ferrari, 2009). With a maximum intensity platoons, vehicles need to stop because lane changing cannot be executed (Figure 27). Stops of vehicles do not occur in real traffic. However, in the simulation model it gives an indication that vehicles cannot perform a lane change due to other vehicles on the desired lane. Platoons have a length of 69,75 meters which affects the merging and diverging behavior of other road users and platoons itself. Traffic conflicts can arise which has a negative impact on the overall traffic safety within this area.

Platooning increases the traffic flow within the area and reduces the queue delay of cars. Thus, the size of a platoon does not affect the overall speed of vehicles. The traffic safety within the weaving area is affected in a negative way by platoons compared to the situation with single trucks. Platoons have difficulty to merge and therefore need to stop. Platoon can form a blockage and this can increase the amount of traffic conflicts.

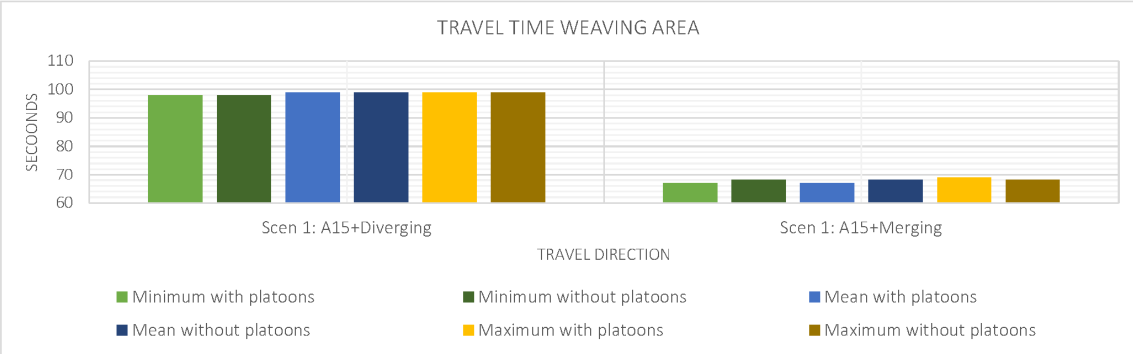


Figure 21: Travel time off all vehicles within the weaving area of scenario 1, morning peak hour

Figure 22: Velocity on each traffic lane within the weaving area during scenario 1, morning peak hour

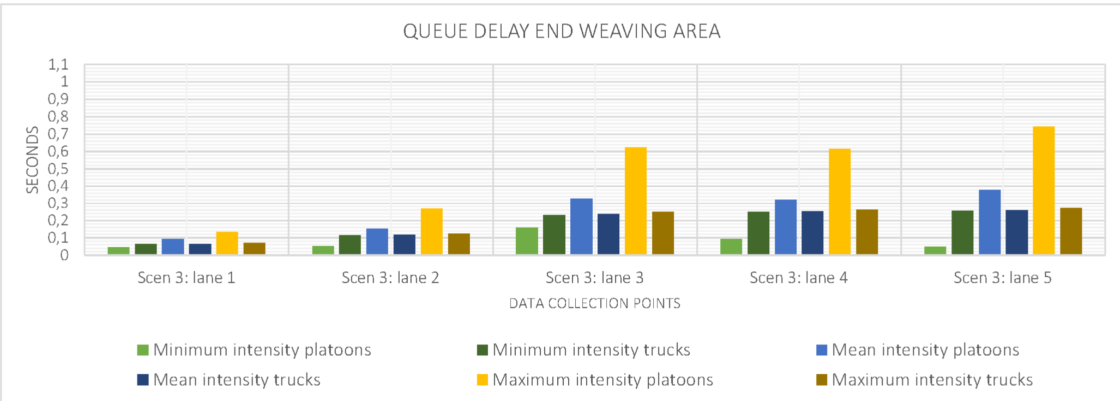
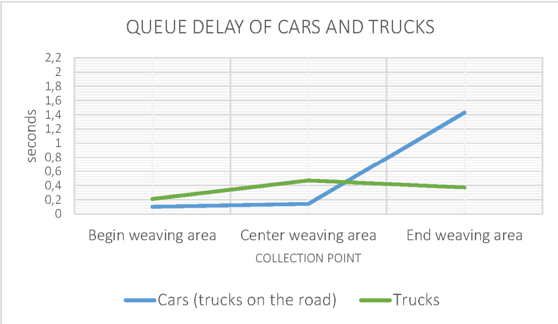


Figure 23: Queue delay of scenario 3 at the end of the weaving area. In scenario 1 and 2 the trend of the queue delay is the same Appendix B5, Figure B 7)



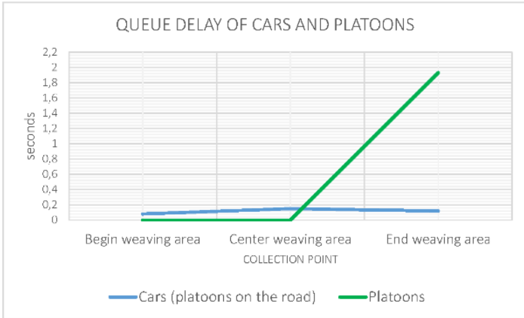


Figure 24 & Figure 25: Queue delay of cars, trucks and platoons due to lane changes within the weaving area during scenario 3 with a maximum intensity of platoons

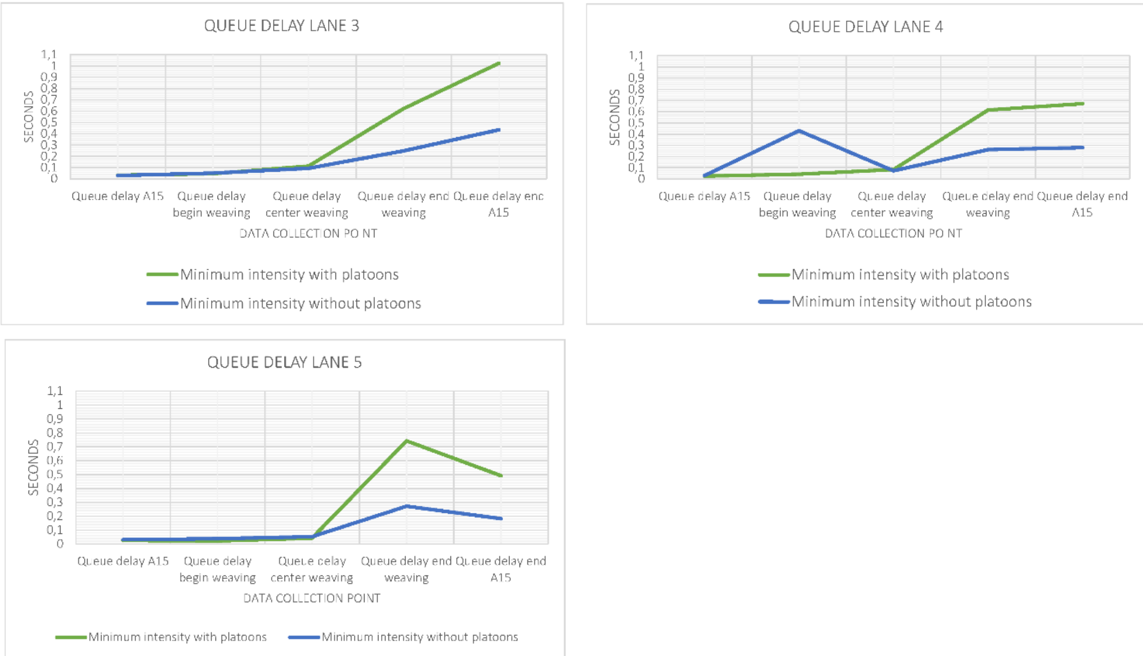


Figure 26: Queue delay at the three traffic lanes which is the main road of the A15 corridor. The merging and diverging lane are a part of one of these traffic lanes

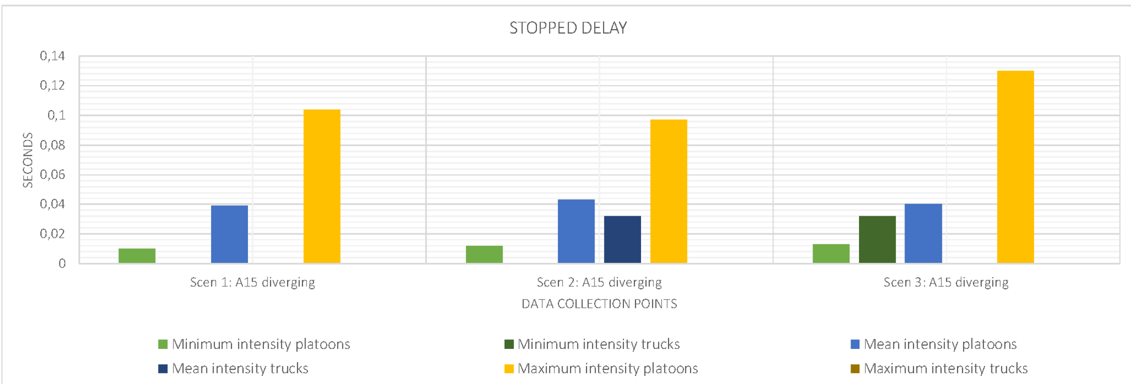


Figure 27: Stopped delay at the end of the weaving area when vehicles have the travel direction diverging

5.4.2 IMPACT OF PLATOONING ON MERGING AREA

The traffic flow near the merging area is increased with a minimum intensity of platoons. With a mean and maximum intensity the travel time is decreased. The velocity with a maximum intensity of platoons is decreased at the end of lane 2 which does not enhances the overall travel time within the merging area (Figure 29 & Figure 30). There is a marginal differences between the scenarios with platoons and without platoons. Thus, platooning has slightly more impact than single trucks on the A15 corridor because platoons cannot overtake each other and vehicles can increase their overall speed on the left lane.

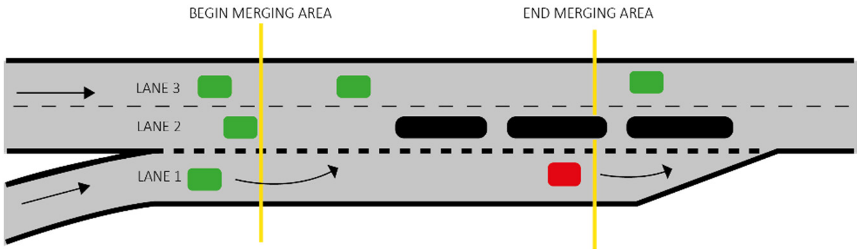


Figure 28: Merging area on the A15 corridor with the data collection points

Merging is an exceptional maneuver and vehicles on the main road have priority compared to the vehicles in the merging lane. With a maximum intensity of platoons and trucks on the road the velocity decreases. If the situation with trucks on the road is compared to the situation with platoons on the road, the velocity decreases more with platooning at the end of lane 1 (Figure 30). Compulsory lane change is not taken into account in the simulation model and vehicles obey the rule that the traffic on the main road has priority compared to the vehicles on the merging lane. However, the low velocity can have an impact on the queue delay and can increase traffic conflicts. The queue delay increases when vehicles cannot perform a lane change and need to accelerate or decelerate at the end of the merging lane. Queue delay occurs for every χ intensity of platoons on the road (Figure 31). This indicates that merging with platoons on the road is difficult and increases compared to the scenario when single trucks drive on the road. This is especially the case when the ratio cars is higher in a scenario (Appendix B1, Table B 1).

Cars cannot merge into the main corridor properly due to the fact that the vehicle intensity is high on the A15 corridor and platoons are 69.75 meters long with a short inter vehicle distance (Figure 32 & Figure 33)(Appendix B4, Figure B 10). This increases the queue delay at the end of the merging area (Figure 31). Additionally, the queue delay of platoons increases with a minimum and mean intensity of platoons on the road. This indicates that merging for platoons is difficult and a suitable gap of approximately 69 meters cannot be found. During peak hours the queue delay increases. Within these hours the ratio cars-trucks is at its highest. For example in scenario 3, the ratio cars (92%) - trucks (8%) differs compares to the ratio cars (81%) - trucks (19%). When more cars are on the road with different car-following behavior merging is more difficult and a queue delay is more likely to occur (Durrani, Lee, & Maoh, 2016). Hence, the length of the platoon and its short inter vehicle distance has a large impact on the merging behavior of cars but also on platoons itself. This can increase the chance of a moving bottleneck.

Vehicles merge into the adjacent lane with a lower speed compared to the main road. A variation in speed can affect the traffic safety (Michalaki, Quddus, Pitfield, & Huetson, 2016). Vehicles stop at the end of the merging lane and this can influence the gap acceptance of a vehicle. With the short inter vehicle distance of a platoon and a high intensity of vehicles on the road traffic collisions can increase. Thus, at the end of the merging area the traffic safety will decrease with platooning on the road (Appendix B4.2, Table B 2) (Figure 34).

Thus, platooning slightly enhance the traffic flow compared to singe trucks on the A15 corridor. Nonetheless, this is highly influenced by the merging behavior of vehicles and especially platoons have a problem to merge onto the main road. Platooning increases road capacity and do not overtake each other. Platooning concentrates the amount of trucks on the road thus less vehicle might be influence of the presence of platoons. Hence, the safety within the merging area is increased.

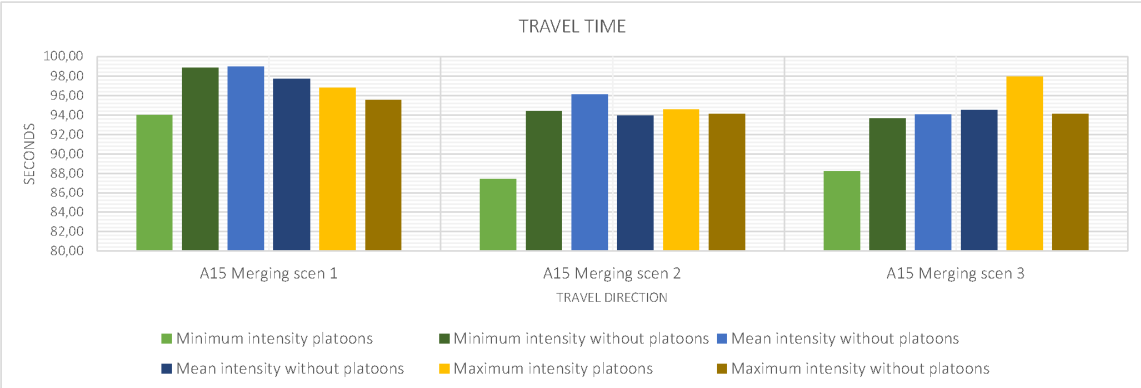


Figure 29: Travel time within the merging area. Scenario 1 is given as a representation for the other scenarios

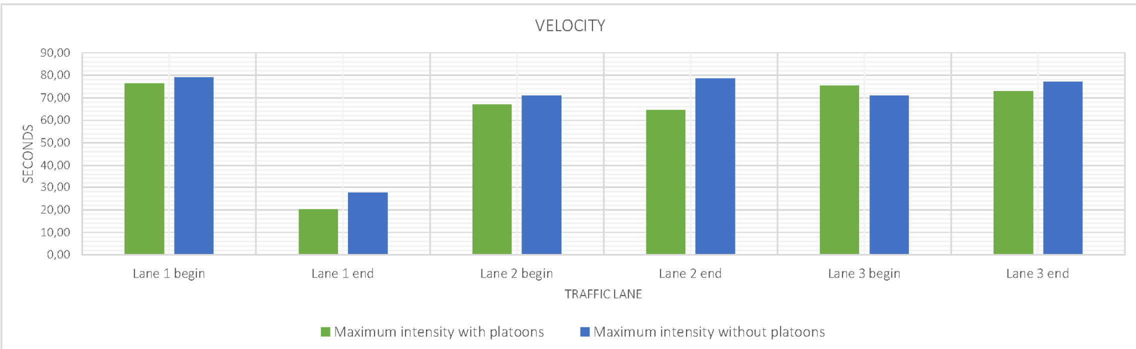


Figure 30: Velocity within the merging area during scenario 1 with a maximum intensity of platoons on the road

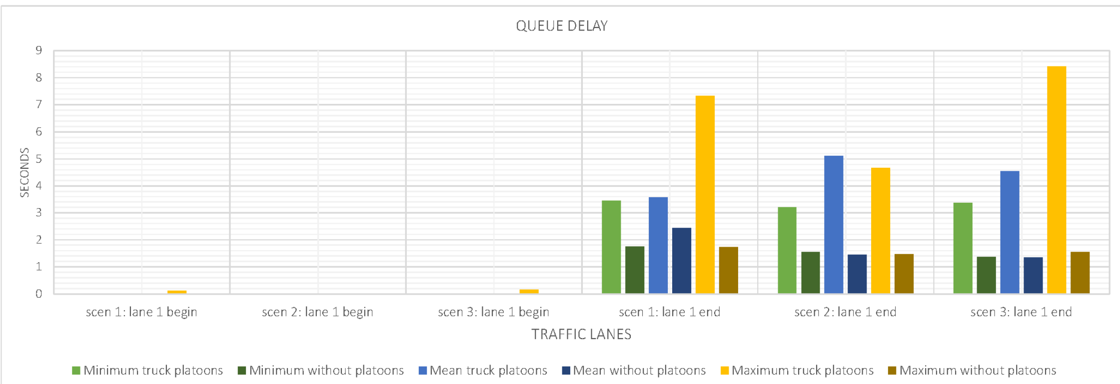


Figure 31: Queue delay of the total traffic stream at the merging lane of every scenario

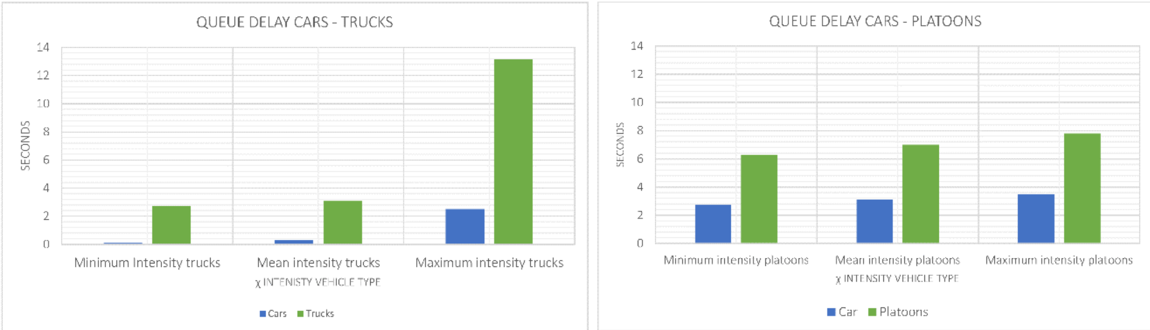


Figure 32 & 33: Queue delay per vehicle type of scenario 3 with a maximum intensity trucks/platoons on the road. The decrease of trucks is because a platoon is considered as a single entity.

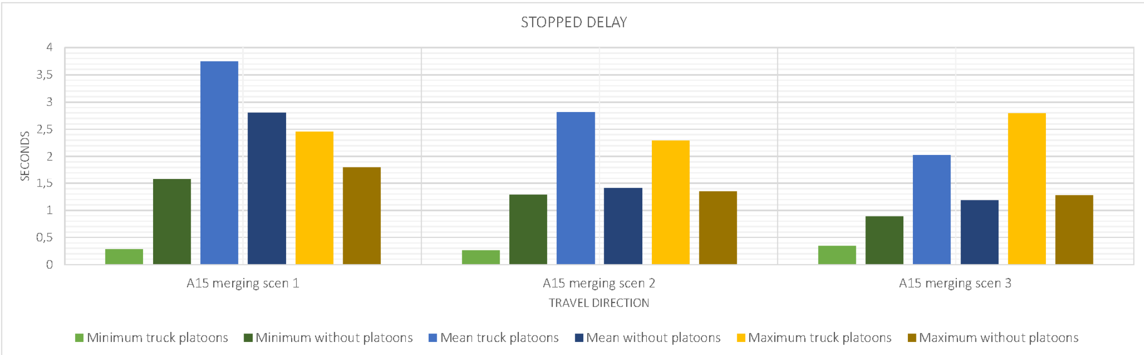


Figure 34: Stop delay of vehicles in every scenario

5.4.2 IMPACT OF PLATOONING ON DIVERGING AREA

The driving behavior within merging and diverging areas is different (Liu, Li, & Jia, 2014; Jongenotter, 2016). Vehicles are far upstream the main road informed when the diverging lane starts. With merging vehicles first need to scan their surroundings, characteristics of the main road and are forced to change lanes to the main road.

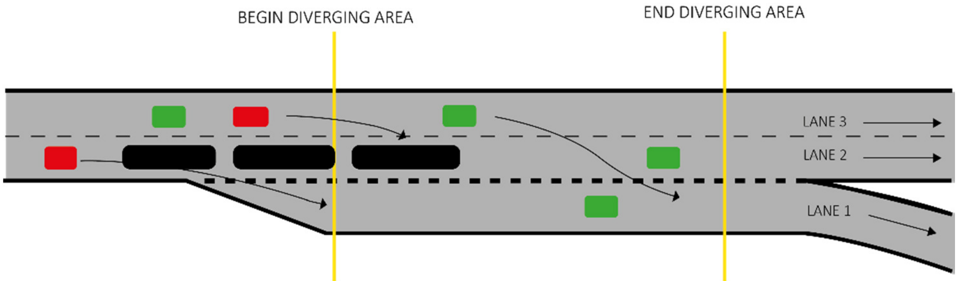


Figure 35: Diverging area of the A15 corridor with its data collection points

Platooning increases the road capacity and can benefit the overall traffic flow and safety (Trantow, Stieger, Hees, & Jescke, 2013). In scenario 2, the travel time with platoons and with single trucks is equal. The amount of platoons within the diverging area has the most impact on the traffic flow. This indicated that vehicles cannot diverge properly because platoons are driving on lane 2 and vehicles need to decelerate before and within the diverging area to diverge (Figure 37 & Figure 38)(Appendix B4, Figure B 12). In scenario 1, vehicles decelerate at the beginning of the diverging area (Appendix B5.3, Figure B 10). This type of behavior affects the overall traffic flow and travel time. Platooning within a diverging area is only beneficial during the afternoon peak hour and daytime off peak hour.

The deceleration behavior can have an impact on the queue delay of vehicles. These fluctuations can cause a moving bottleneck and spillbacks. At the beginning of the diverging area the queue delay of vehicles increases and this causes a moving bottleneck up to 150 meters before the diverging lane (Figure 37). Platoons cover a large area on a traffic lane and within the diverging area this type of vehicle can be a blockage for other road traffic. The velocity between cars and platoons is different. 1200 meters and 600 meters up front the diverging lane vehicles get information when they need to diverge. Vehicles can already start anticipating and perform the desired lane change. The differences in speed on lane 2 can increase the queue delay before the diverging area. Additionally, vehicles need to decelerate and accelerate to merge on lane 2 before or after the platoon (Figure 38).

Fluctuations in velocity and acceleration and deceleration behavior of vehicles can increase the amount of traffic conflicts and dangerous driving behavior. Cars merge on the diverging lane as the last moment and need to accelerate or decelerate in a short period of time. With every intensity of platoons on the road the stop delay increases compared to the situation with single trucks on the road. This decreases the traffic safety within the diverging area. Currently, merging and diverging on roads were the ratio of trucks is high is already difficult (Hottentot, 2017). With a minimum intensity of platoons on the road the traffic safety is affected to a lesser extent compared to a mean and minimum intensity of platoons on the road (Figure 41). Thus, it can be stated that with platooning the traffic safety is decreases because of the fluctuation in velocity as well as the acceleration and deceleration behavior of vehicles.

To conclude, the traffic flow within the diverging area is in overall not affected by platooning compared to the situation with single trucks. Platooning increases the road capacity within this traffic situation and the overall travel time is increased. However, the traffic safety and efficiency within this area is affected by platooning due to length and short inter vehicle distance. Platooning forms a blockage which can increase traffic conflicts and the queue delay of vehicles. Platooning can enhance dangerous driving behavior when vehicles want to perform a lane change to the diverging lane.

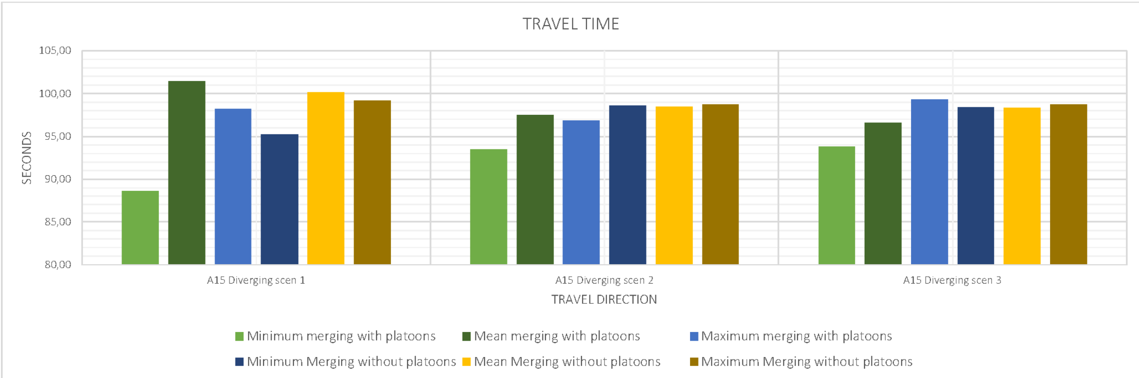


Figure 36: Travel time when vehicles need to diverge of the A15 corridor

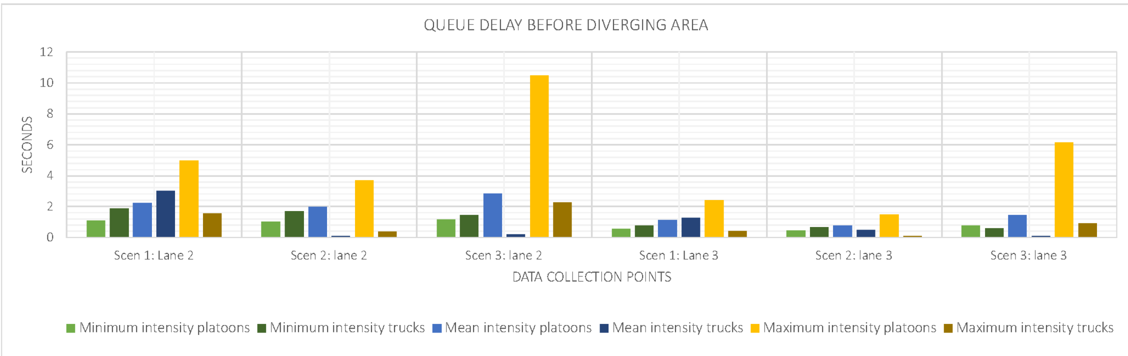


Figure 37: Queue delay 150 meters before the diverging area in scenario 1

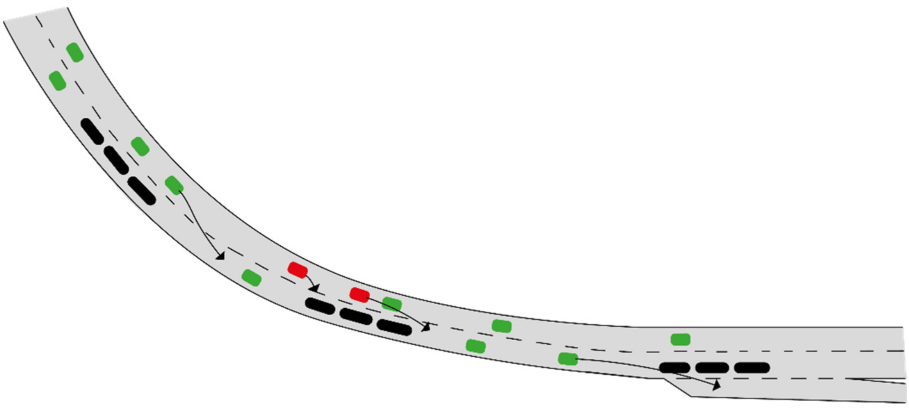


Figure 38: Queue delay which can occur before the diverging lane due to platooning and a high intensity of vehicles on the road

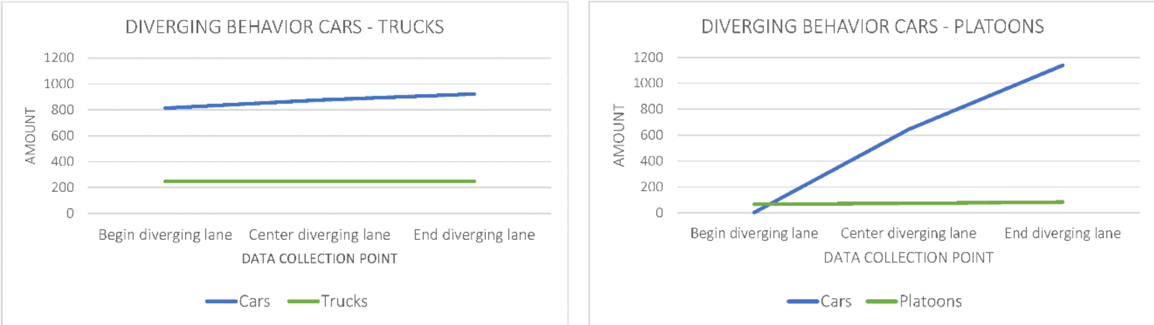


Figure 39 & 40: The amount of vehicles on the diverging lane. The data is collected at the beginning of the diverging lane and at the end of the diverging lane

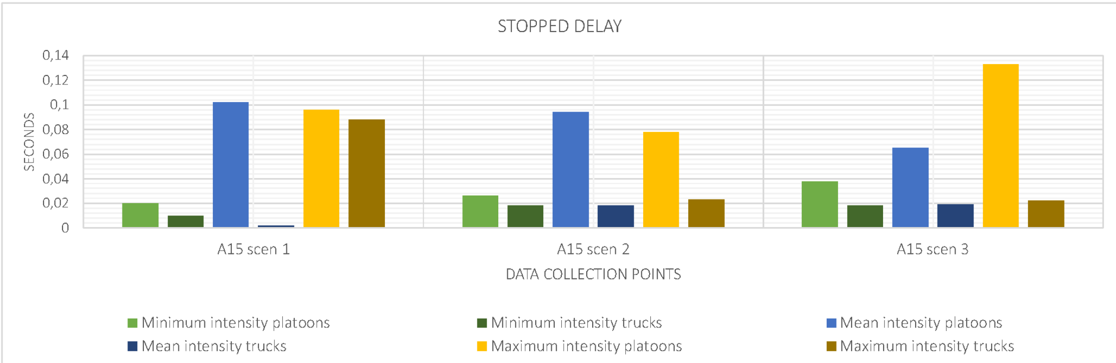


Figure 41: Stopped delay within the diverging area of every scenario

5.5 CONCLUSION

The traffic situation weaving, merging and diverging are analyzed on the impact of large scale truck platooning. Currently, single trucks have already an impact on the A15 corridor and the prediction is that with platooning that the traffic management is optimized. The results showed that:

- Traffic flow is optimized with platooning in every traffic location;
- Performing lane changes becomes more difficult when platoons drive on the road especially for cars within the merging area;
- Lane change performance is optimized at the beginning of the weaving area and decreased at the end of the weaving area. A ‘snowball’ effect occurs to the other lanes;
- Minimum intensity of platoons is beneficial for traffic efficiency and partially for the safety in every traffic location;
- Maximum intensity of platoons increases traffic conflicts and the queue delay on the road due to the amount of platoons and the small inter vehicle distance;
- Platooning affects the merging and diverging behavior of other platoons.

All these results showed that platooning with a mean and maximum intensity is not beneficial for the efficiency and safety. A small inter vehicle distance of platooning has a large impact on the traffic management within weaving, merging and diverging areas. Additionally, the fluctuations in velocity and performing a lane change would not be beneficial for the overall emission of traffic within these areas. The literature study in Chapter 2 stated that platooning will increase throughput, capacity and safety. This is the case with a minimum intensity of platoons within an excessive traffic locations. However, with a mean and maximum intensity of platoons these benefits can partially be met. Traffic flow is indeed increased but safety and efficiency is decreased and should be further analyzed.

Overall result

The three traffic location are analyzed on three criteria: traffic flow, efficiency and safety. The results of the experiments are ranked on a scale from 1 - 5. This type of scale is derived from Best Worst Scaling (BWS). The preferred and least preferred results are ranked according to a set of available options. Tipping points of 25% and 50% are defined because reducing traffic flow and efficiency by 50% is not preferred and serious actions should be taken into account.

- *- - Severe impact*: Platooning has a severe impact on the traffic flow, efficiency and safety. Results are decreased with > 50% compared to the base situation with single trucks;
- *- Impact*: Platooning has a negative impact on the traffic flow, efficiency and safety. The results of the experiments are decreased <50% of the results from the base situation with single trucks;
- *O impact is equal to base situation*: Platooning is not increasing or decreasing on traffic flow, efficiency and safety. Extra analysis needs to be carried out to understand the full impact of platooning on a human and engineering level;
- *+ Positive:* Platooning is increasing the traffic flow, efficiency and safety. The results of the experiments are decreased within a range of < 25%;
- *++ Improving:* Platooning is beneficial for the traffic flow, efficiency and safety. The results of the experiments are increased with > 50% compared to the base situation.

The results of the three traffic locations on the three criteria are sorted on a scale from 1 - 5. Table 14 gives an overview of the overall conclusion of the impact of large scale truck platooning within weaving, merging and diverging areas.

Table 14: Overview of the impact of platooning on the traffic management at the A15 corridor

	Weaving			Merging			Diverging		
	Flow	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*	*Flow*	*efficiency*	*Safety*
Minimum intensity	+	++	o	+	--	++	+	+	-
Mean intensity	+	-	--	+	--	--	+	o	--
Maximum intensity	+	--	--	+	--	-	+	--	--

* *- Impact* *o Impact is equal to base situation* *+ Positive*
-- Severe impact *++ Improving*

5.6 DISCUSSION

The experiments are based on specific traffic locations on the A15 corridor with a three truck platoon with a inter vehicle distance of 6.7 meters. The results of the experiments gave an indication what the impact of large scale truck platooning is on the traffic management on the A15. Overall the traffic flow is increased with platooning but the efficiency and safety is still a problem. The fluctuations in acceleration and deceleration behavior of vehicles can have an impact on the fuel efficiency of platoons and the overall emission of all vehicles.

The platoon that is used in the simulation model is a three truck platoon with a fixed inter vehicle distance of 6.7 meters. Certain assumption are made to analyze the impact of platooning on the traffic management. This can be considered as the most optimum scenario. According to the literature study in chapter 2, the inter vehicle distance can vary when a non-platoon member drives within the platoon. This can have an impact on the traffic management within these traffic locations.

As mentioned in chapter 3, simulation model do not represent driving behavior in its full extent. Driving behavior is influenced by human and engineering factors. This research only focused on the engineering factors. However, human factors play an important role in traffic management.

Fatigue, stress and psychological state of drivers can affect how well a person is driving and how well specific traffic situations are assessed by the driver itself.

Nonetheless, the results in the experiments give an indication on what the impact of large scale platooning is on the traffic management near complex traffic situations. Traffic efficiency and safety are still two areas which need to be further analyzed. Additionally, the experiments can be expand and human factors should be taken into account.

CHAPTER 6

ROAD STRATEGIES TO ENHANCE TRUCK PLATOONING ON THE A15 CORRIDOR

Truck platooning on the A15 corridor within weaving, merging and diverging area has an impact on the efficiency and safety. The traffic flow is enhanced with platooning. Safety is one of the important issues to develop a sustainable and safe traffic system (Hoogendoorn, et al., 2012).

First, the various traffic management road strategies are discussed in section 6.2. The prediction is that with these road traffic management strategies the safety and efficiency of platooning within weaving, merging and diverging areas can be improved. A description is given of the specific road traffic management strategies in section 6.3. Finally, recommendations are proposed how complex traffic situations can react on truck platooning and possibly in the future to other new vehicle technologies.

6.1 INTRODUCTION

Platooning increases the overall traffic flow within complex traffic locations on the A15 corridor compared to single trucks on the road. The time of the day (scenarios) does not have a large impact on the functioning of platooning on the road. According to the literature study in Chapter 2, road traffic management strategies need to be more dynamic to react on certain trends. In the upcoming years, the dynamics of traffic management can change due to new vehicle technologies. This can enhance the application of new type of road traffic management strategies which can react on specific trends on a social, economic and automotive level.

Certain assumptions are defined according to the literature study in Chapter 2. One important assumption that is defined is the inter vehicle distance of 6.7 meters. With a small inter vehicle distance the fuel reduction is the highest. However, this forces vehicles to perform a lane change in front or at the back of a platoon. In section 6.3, an elaboration is given on this assumption and if it is desired to create such small inter vehicle distances at complex traffic locations.

6.2 ROAD TRAFFIC MANAGEMENT STRATEGIES

To reduce the negative side effects off platooning on the efficiency and safety on the A15 corridor specific road traffic management strategies can be applied. The relation between road traffic management strategies and vehicle technologies are given in Figure 42. Road traffic management strategies should be flexible and an information-ergonomic approach should be followed to develop a safe and more user friendly system. With road traffic management strategies the supply and demand is influenced. The aim is to spread both the traffic demand and the supply on the infrastructure and make better use of it (Hoogendoorn, et al., 2012).

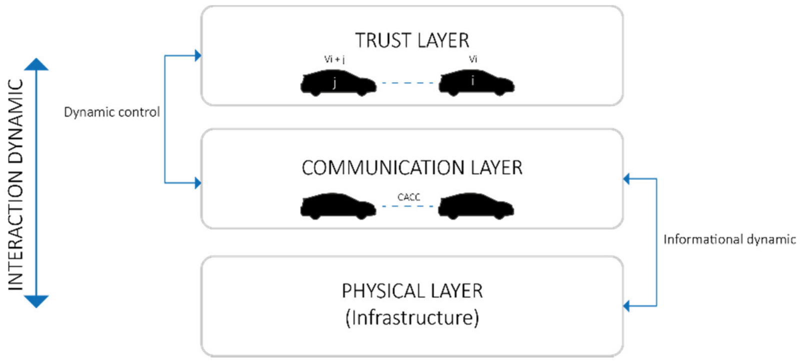


Figure 42: Interacting layers when road traffic management strategies need to be applied. Figure adapted from (Guériau, et al., 2016)

With truck platooning a new type of vehicle will enter the road and this gives a chance to implement new techniques which are subjected to the trends stated in section 2.5 of Chapter 2. Constructing new roads, improving bottlenecks or widening existing roads are the obvious approaches but with these measures drawbacks arise. Optimizing one bottleneck will enhance the bottleneck to appear somewhere else. According to the analysis in Chapter 5, truck platooning increases the traffic flow within weaving, merging and diverging areas. Safety and efficiency is affected by large scale platooning. These negative impacts can possibly be reduced by specific road traffic management strategies. In the literature study, specific road strategies are recommended and researched.

- Connecting vehicle data with traffic data (*Engineering and Human factors*);
- Dynamic traffic management (*Engineering factors*);

The relation between vehicle - human - and technology is shifting. Currently, infrastructure is based on a large part on the human measurement. New vehicle technologies might require new conditions and new possible road strategies could be applied. The prediction is that in the near future autonomous/automated, cooperative, human driven and platoons of vehicles will share the road and current traffic management should be adapted to this transition phase. Platooning uses state-of-the-art technologies. Human driven vehicles are still subjected to the human driving behavior and exogenous variables such as fatigue, stress and weather conditions. Safety is related to the physical environment as well as the perception of the human driver. The proposed road strategies are tested on engineering factors but additional information is given on how the human factor can be influenced as well.

6.2.1 CONNECTING VEHICLE DATA WITH TRAFFIC DATA

Road traffic management strategies can be applied on the supply and demand side. The ratio trucks on the A15 corridor is quite high compared to other highways in the Netherlands. Additionally, trucks drive mostly during the peak hours and daytime off peak hour (Figure 43). The distribution on the network is unbalanced.

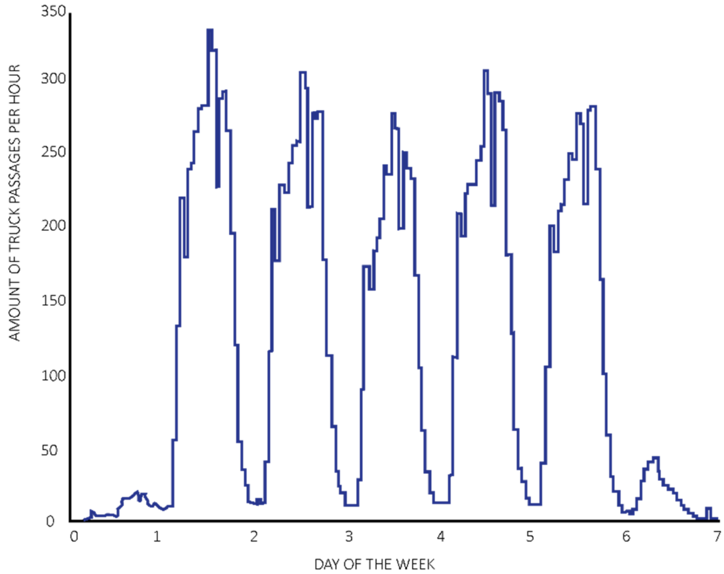


Figure 43: Amount of truck passages per hour in a week. With 0-1 is a Sunday and 6-7 is a Saturday. The gross amount of truck traffic takes place between 7h00 - 18:00. Figure Adapted from (Witteveen+Bos Raadgevende Ingenieurs B.V., 2016)

To shift from driving in peak hours in off peak hours is still challenging. The distribution of goods is influenced by various factors such as supply chain management and the restrictions on work hours of truck drivers (Jongenotter, 2016). With platooning the amount of truck drivers is reduced and platooning in the off peak hours is possible. The vehicle intensity in the off peak hours is low compared to peak hours and day time off peak hour. Within complex traffic locations such as merging, diverging and weaving areas the overall traffic flow, safety and efficiency can be increased by platooning when the intensity is at its minimum.

According to Özgüner et al. (2007) a cooperation needs to be established between the environment and the vehicle. A few example to establish a V2I communication system is by slots and RFID tags placed on the roads. These solutions are mainly based on the technology of 'smart' vehicles. In the transition phase multiple types of vehicles will share the road. With the application a new application emerges: connecting the data of a platoon can be connected to the traffic data. The port of Rotterdam uses the Port Community system, Portbase, which registers data of the supply chain management as well as the traffic data. An example of such a strategy is ramp metering. The demand side of traffic management is regulated which affects the overall traffic management. According to Ran et al (1999) the data of velocity can be used to analyze and predict the movement within complex traffic locations. With new vehicle technologies, new type road traffic management strategies can be applied in a more sustainable and efficient way. Preventing spillbacks and regulate the traffic flow with dynamic speed distributions can be used. Lane changing is one of the most disrupting factors within a traffic flow and this can cause traffic conflicts. Speed distributions have an impact on the efficiency and safety within weaving areas. Lane change performance increases with the introduction of lower speed on highways (Soriguera, Martínez, Sala, & Menéndez, 2017). In dense traffic conditions, low speeds can contribute to elimination of moving bottlenecks and possible spillbacks. Additionally, the heaviest truck within a platoon defines the overall velocity of the platoon. If this type of data and the known capacity on the road is connected to each other, movements within complex traffic locations can be guided. This can increase the overall efficiency and safety within these areas.

Vehicle technologies are rapidly increasing and at the same time the number of older drivers on the road is increasing (Owens, Antin, Doerzaph, & Willis, 2015). Driving behavior can become more difficult and the perceptual, physical and cognitive challenges will increase. With the decrease of velocity on highways when the intensity of platoons is at its maximum, older drivers have an opportunity to analyze their surrounding and increase the feeling of safety.

Output of the experiment: Speed distribution

Speed limits near complex traffic situations is not an uncommon phenomenon (Hoogendoorn, et al., 2012). Trucks drive with a lower velocity compared to cars. Platoons have an inter vehicle distance of 6.7 meters which is forcing vehicles to accelerate or decelerate to the front or behind the platoon when vehicles want to perform a lane change. With the speed reduction the difference in velocity between these two type of vehicles can be decreased.

The speed limit for all vehicles is set on 85 kilometers/hour. This is not a hard constraint and vehicles can increase their velocity above this limit to perform lane changes. Each road strategy is analyzed on the travel time, queue delay and stopped delay of vehicles. Implementing of specific road strategies have to meet specific requirements. Therefore, the results in Table 15 give an approximation of what the impact is of this type of road traffic management strategy, but these still need to be analyzed further.

The difference in velocity between vehicles is decreased and this might influences the gap acceptance. Vehicles have more opportunities to merge of diverge into the adjacent lane within merging and diverging areas. Within weaving areas the efficiency and safety is partially increased. The interaction between cars and trucks is asymmetric and the reduction in velocity does not decrease the negative effects of this interaction. Within weaving areas the size of the platoon and the short inter vehicle distance is still of influence and the reduction in speed is not a solution within this complex traffic situation. Thus, lower speeds need to be introduced to optimize the traffic safety and efficiency within this area. The exact speed should depend on the traffic characteristics of that specific day.

Table 15: Road strategy Speed reduction. A comparison between trucks with a speed limit (ν = max 85 km/h) with platoons on the A15 corridor which obey the current traffic characteristics

	Weaving			Merging			Diverging		
	Flow	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*
Minimum intensity*	o	--	--	-	o	+	--	-	++
Mean intensity*	o	--	-	-	+	++	--	o	o
Maximum intensity *	o	+	++	-	++	+	--	+	--

** Appendix C1.1 gives an elaborated analysis of the three traffic situations*

6.2.2 DYNAMIC TRAFFIC MANAGEMENT

The infrastructure near complex traffic locations is designed according to specific regulations and based on the current vehicle composition on the road (Ministerie van Infrastructuur en Milieu, 2015). Dynamic traffic management can be defined as a way to organize and optimize infrastructure in such a way that infrastructure and traffic management can react on trends. An example of such a strategy is the plus lane. When the road capacity is increasing on a highway the emergency lane becomes an extra traffic lane. This type of strategy can also be applied to the A15 corridor in a different way:

- Dynamic merging and diverging lanes;
- Platoons drive on the left side of the road.

Lane change performance is influenced by road geometry, vehicle size and the psychological state of drivers (Marczak, Daamen, & Buisson, 2013). When the road intensity increases during peak hours, merging and diverging lanes can become longer. The prediction is that there are less fluctuations within the merging and diverging area because vehicles have more time to find a suitable gap on the main road.

Platoons can form a blockage near complex traffic locations when lane changing needs to be performed. The on and off ramps on the A15 corridor connects port terminal with the A15 corridor and lane changing of trucks need to performed. Nonetheless, the left lane can be assigned as a dedicated lane for trucks. Lane change behavior of other vehicles might be less influenced by the length of a platoon. This can increase the safety because drivers are not influenced by the platoon and possible stress due to performing a lane change can be decreased. Note is that the platoons need guidance when these vehicles need to perform lane changes to the outer most left lane. A possible solution for this is that lane changing to the outer most left lane is performed after merging and weaving areas when numerous of lane changes by vehicles occur less.

Output of the experiment: Longer merging and diverging lanes

Longer merging and diverging lanes can be applied to increase the efficiency and safety. Longer merging and diverging lanes give an opportunity to vehicles to find a suitable gap in the main road. The road geometry, characteristics of vehicles and surroundings can be analyzed longer and more extensive which might increase the traffic safety and efficiency (Table 16).

The merging and diverging lane are increased with an extra 50% of the total length of the current merging and diverging lane[2]. This road strategy is only applied on the merging and diverging lane. The behavior within weaving areas is more complex and only when vehicles want to diverge, problems occur with the traffic efficiency and safety. It is clear that with a longer merging and diverging lane the overall traffic management is decreased on every criteria. The reason for this can

[2] Merging lane in the current situation is 180 meters, with the adaption the merging lane becomes 270 meters. The diverging lane was in the current situation 120 meters and with the adaption the diverging lane becomes 180 meters

be that vehicles do not oversee the merging lane and expect it as a new lane. Infrastructure is designed according to strict rules which takes into account the vehicles as well as the safety of human drivers. The length of merging and diverging lanes can enhance confusion what the aim of the traffic lane is; a continuation of the main road or a diverging or merging lane.

Table 16: A comparison with the situation were longer merging and diverging lanes are applied with platooning and the situation were platoons obey the current traffic management on the A15 Corridor

	Merging			Diverging		
	Flow	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*
Minimum intensity	-	--	--	-	--	--
Mean intensity	o	--	o	+	+	--
Maximum intensity	-	--	--	-	--	--

** Appendix C1.2 gives an elaborated analysis of the three traffic situations*

In order to apply this type of strategy the designing of the dynamic merging and diverging lane is important. Drivers need to be informed that it is possible use the extra length of the merging or diverging lane. To define the dynamic merging and diverging lane traffic signs can be applied. For example the signs when a plus lane is opened at peak hours on a freeway (Hoogendoorn, et al., 2012).

Output of the experiment: Trucks drive on the left side

Most of the vehicles on the A15 corridor can be defined as destination traffic. The ratio trucks is high and the A15 corridor is the only connection of the Maasvlakte II to the hinterland. The aim of the highway is quite clear and trucks/platoons can drive on the left lane because these vehicles drive a longer distance and do not need to perform numerous of lane changes.

Table 17 gives an overview of the results from the road strategy compared to the situation where platoons obey the current traffic management. In weaving section multiple lane changes need to be performed and platoons can be a blockage. With platoons on the outermost left lane the efficiency and safety is increased. If these results are compared to merging and diverging area the overall traffic management is reduced. A reason for this can be is that this is a 2x2 traffic configuration. Thus, vehicles have only one lane to drive on where also merging and diverging of vehicles takes place with a lower speed. If a platoon merges onto the main road with a low velocity a moving bottleneck can occur (Figure 44).

Table 17**:** A comparison with the situation where platoons drive on the left side of the road compared to the situation where platoons obey the current traffic management on the A15 Corridor

	Weaving			Merging			Diverging		
	Flow	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*
Minimum intensity	o	-	o	-	o	--	-	--	--
Mean intensity	o	+	++	o	o	--	-	--	--
Maximum intensity	o	++	++	-	-	--	-	--	--

** Appendix C1.3 gives an elaborated analysis of the three traffic situations*

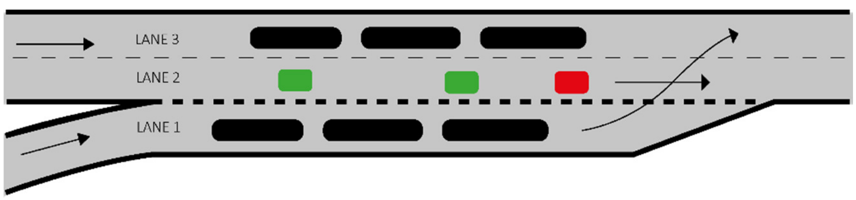


Figure 44: Conflict area within the merging area when trucks need to drive on the left lane

The aim of this road strategy is to decrease the impact of large scale truck platooning on the overall performance of the network. To decrease the conflicts and to increase the proper functioning of this road strategy specific paths which platoons can follow to the dedicated lane should be analyzed. A possible solution is that within the specific traffic conflicts platoons only perform on lane change. After the traffic location multiple lane changes to the desired lane can be performed by the platoon. Note that this can create shockwaves on the overall network. To implement this strategy the most optimal path of a platoon should be analyzed and calculated.

6.3 SMALL INTER VEHICLE DISTANCE OF A PLATOON

The inter vehicle distance is set on 6.7 meters. This will force vehicles to perform a lane change up front or behind the platoon. The fuel reduction is at its highest with this inter vehicle distance but it creates fluctuations in traffic flow. Hence, it is possible that the fuel reduction with an small inter vehicle distance of 6.7 meters cannot even be met. The experiments showed that the traffic safety is reduced with platoons with a small inter vehicle distance. Traffic safety is important to develop and maintain a sustainable and safe traffic system (Hoogendoorn, et al., 2012). The inter vehicle distance can be increased and vehicles have the possibility to merge or diverge through a platoon. Note that when a non-platoon member merges into a platoon, a platoon will establish a new desired distance to the non-platoon member. This can cause shockwaves.

6.4 FRAMEWORK TO OPTIMIZE THE INFRASTRUCTURE NEAR THE PORT AREA

Large scale platooning has an impact on the traffic management. The efficiency and safety are reduced in complex traffic locations. To implement road strategies to decrease these negative effects, various factors should be taken into account. On an engineering level road strategies such as lowering speed, trucks drive left instead of right can be beneficial. Left lane driving of trucks can be compared to traffic management strategies where truck have a dedicated lane. According to Xun et al. (2011) this strategy will reduce the amount of lane changing and enhances safety on freeways. Left lane driving can be beneficial for trucks but a closer look and further analysis needs to be done in order to understand when trucks want to diverge and merge. Speed distributions are already applied on the Dutch infrastructure where the road capacity is increased during the peak hours (Hoogendoorn, et al., 2012).

Human factors are an important element in relation to traffic management. Driving behavior is defined by age, gender, psychological state etcetera (Wegman, 2016). Additionally, the Dutch traffic management is carefully designed by a specific set of rules and regulations. The road strategies that are proposed in the previous paragraph do not take all these regulations into account. The proposed road strategies are an approximation on how the impact of large scale truck platooning can be decreased.

Three traffic locations are analyzed on what the impact is on large scale truck platooning. Each of these locations has its own characteristics which influences the driving behavior. Nonetheless, the implemented road strategies should benefit all these traffic locations with its characteristics. Table 18 gives an overview which type of road strategy can be applied by which intensity of truck platoons on the road. Increasing efficiency and safety is crucial to create a sustainable and safe traffic system. The advantages of platoons should be enhanced by the infrastructure as well as the traffic management itself.

Table 18: An indication on which criteria the road strategies should be applied on

Intensity of platoons	Traffic flow	Efficiency	Safety	Road strategies
Minimum			x	*Inform other road users by road side units or send them a notification. Apply the road strategy based on the human factor*
Mean		x	x	Decrease the difference in driving behavior by decreasing the overall velocity. Additionally, give information to human drivers
Maximum		x	x	Decrease the difference in driving behavior by adjusting overall traffic speed, give information to human drivers. Apply platooning partially outside the peak hours and test more with left side driving.

** Green indicates that road strategies should be focusing on these criteria*

6.5 DISCUSSION

The road strategies that are proposed can only give an indication what the effect is on the three defined criteria. Road strategies need to meet numerous of requirements which are depended on specific criteria (e.g. turns in merging, diverging lanes, length, width, visibility etc.). In the experiments these regulations are not taken in account to its full extent. Platoons within simulation models are difficult to calibrate and validate and therefore applying road strategies to enhance this type of mobility is still difficult.

Further analysis needs to be done to understand the full impact of large scale platooning on the traffic management near complex traffic situations. Human factors should be taken into account because this is of influence on the driving behavior. With the requirements from the human measurement and the requirements on an engineering level, well designed traffic management strategies could be applied in relation to large scale platooning.

CHAPTER 7

CONCLUSION, SCIENTIFIC RELEVANCE AND FURTHER RESEARCH

Platooning is a topic which is in high development within the automotive industry as well as on an economical and societal industry. The analysis in chapter 5 showed that platooning on a large scale has impact on traffic efficiency and safety. In the upcoming years a closer look has to be given to the full implementation of platooning on the road.

This chapter will discuss the final conclusions, recommendation and the scientific relevance. First in section 7.2 the scientific relevance is discussed. The six sub question are answered in Section 7.3. The main research question is answered in Section 7.4. Platooning is influenced by various factors and is hard to implement in a simulation model. The study in this research is based on several assumption and did not take all factors into account. An evaluation of this research is discussed in section 7.5.

7.1 INTRODUCTION

Lots of studies and pilots are currently begin executed to understand the behavior and impact of platooning. Little research has been done on the impact of large scale platooning when there are various types of vehicles on the road. The aim of this research was to predict the impact of large scale truck platooning on the traffic performance within three traffic locations. With the results the impact of platooning in a mixed environment can be understand better and the connection is made between road traffic management strategies and platooning. Traffic management should react on a changing environment.

7.2 SCIENTIFIC RELEVANCE AND FURTHER RESEARCH

Numerous of studies are available in the field of truck platooning in relation to technology and supply chain management and in the field of driving behavior in relation to single trucks. However, there is a research gap which combines these two research fields. Traffic management is strongly related to the vehicle itself and the human measurement within the traffic system. Excessive traffic can lead to the reduction of the benefits of platooning (Larsson, Sennton, & Larson, 2015). With the application of large scale truck platooning it is possible that the benefits cannot be met and only leads to negative effects.

Through this research the impact of platooning on the overall traffic performance on Dutch highways is made more visible. It is focusing on the transition phase where ‘smart’ vehicles (truck platoons) and human driven vehicles are sharing the road. This transition phase is for many stakeholders (distribution companies, society, Dutch government) still not clear and what their role in it will be. The Dutch government is currently adjusting laws and regulation to allow testing on public roads (Jongenotter, 2016; Dodemont, 2016). With analysis of the impact of platooning on complex traffic locations on highways a possible translation can be made to other complex traffic locations e.g. cities.

This research gave insight that certain advantages of platooning can be met but further analysis should be done in order to obtain the desired traffic safety and efficiency. The safety is only analyzed on an engineering level and traffic management strategies can be partially on these results. However, the next step is to also include the human factor by analyzing the driver behavior in a driving simulator where truck platoons are programmed in. With this research and further research the gap between the technology and traffic management could be reduced and an overall opinion on what still needs to be done to enhance large scale truck platooning in relation to traffic management can be developed.

7.3 CONCLUSION: RESEARCH SUB QUESTIONS

To execute this specific research first six sub question are formulated to address the factors which are important in relation to truck platooning. Each of these sub question is answered separately in the following paragraphs.

7.3.1 Which requirements are needed for truck platooning?

Trucks that drive in a platoon are equipped with lidars, radars and inter vehicle communication systems such as CACC. The longitudinal and lateral behavior of all three trucks within a platoons is equal. According to various literature, 1.2 meters of inter vehicle distance results in a higher fuel reduction. This is an optimal inter vehicle distance and an inter vehicle distance of 6.7 meters can be achieved already (Martens & Beenakkers, Truck platooning, 2017). Trucks within a platoon are communicating by CACC and this is influenced when vehicle merge into the platoon. The safety distance to the non-platoon vehicle is established in the platoon (Ploeg, 2014). This can be an influence on the overall traffic flow and increase moving bottlenecks and spillbacks.

7.3.2 How does truck platooning affect driving behavior of other road users?

Driving behavior is influenced by engineering and human factors (Michalaki, Quddus, Pitfield, & Huetson, 2016). Engineering factors are road geometry, width of lanes, vehicle sizes and lengths. Human factors are: psychological state, fatigue, age etcetera. All these factors are an influence on the driving behavior of the vehicles itself but also can have an impact on the driving behavior of other vehicles. Other vehicles will overreact and decelerate or accelerate. This can increase traffic conflicts and can creates shockwaves.

Weaving and merging areas have numerous of lane changes and this can affect the traffic flow within these areas (Marczak, Daamen, & Buisson, 2013; Liu, Li, & Jia, 2014). The relation car-trucks is asymmetric and this is especially influencing the lane change behavior of vehicles (Durrani, Lee, & Maoh, 2016; Ferrari, 2009). The car-following model is different between cars and trucks and trucks drive with a constant speed (Ossen & Hoogendoorn, 2011). The complexity of the driving task has an influence on the longitudinal driving behavior (Hoogendoorn, van Arem, & Hoogendoorn, 2012). The car-following for a truck and car is different and different safety measures need to be taken into account. The impact of a short inter vehicle distance of a platoon can be extensive.

7.3.3 Which road strategies can be applied in order to guarantee traffic flow, efficiency and safety?

In the Netherlands various road strategies are applied to increase the road safety. A few examples are: ramp metering, route control and plus lanes. With new emerging technologies in the automotive industry, new and dynamic road strategies can be applied. Traffic management is influenced by trends and need to adapt and react on these trends. Road strategies which uses data and are dynamic can increase the adaptation of traffic management to society and its environment. The following road traffic management strategies could be implemented:

- Left lane driving of trucks;
- Dynamic merging lanes;
- Various speed distributions.

All these road traffic management strategies are implemented with the intention that traffic data and supply chain data of the trucks can be connected and these road traffic management solutions are dynamic and can react to trends.

The road strategy '*left lane driving of trucks*' has some challenges with implementing. Within weaving, merging and diverging areas trucks need to perform multiple lane changes compared to the scenario where trucks only have to perform one lane change to drive on the main road. Within these areas and this road strategy specific guidance, speed reductions, optimal path finding need to be applied. Another possibility is that trucks perform lane changes to the outermost left lane after the complex traffic locations. Left lane driving of truck is considered as a possibility within the transportation sector (Dodemont, 2016; Jak, 2016). However, further analysis needs to be done in order to apply this road strategy.

7.3.4 What is the traffic flow management of the A15?

The ratio trucks-cars differ on the A15 corridor compared with other roads in the Netherlands. Traffic data is collected from SmartPort and consists of: vehicle type, intensity and velocity. During the day the intensities for cars and trucks were the highest. Three scenarios were constructed to represent the peak and off peak hours on the A15 corridor. The velocity on the A15 corridor is relative low and quite under the maximum speed of 100 kilometers/hour.

7.3.5 Which data is needed an necessary to set up the simulation model

Simulation models can help to understand driving behavior and the implementation of road strategies. The simulation model that can be used is the microscopic simulation model VISSIM. VISSIM has numerous of parameters and the following parameters needed to be adjusted: intensity, speed distribution, headway time, acceleration/deceleration distribution, look ahead and look back distance. Calibration and validation of simulation models is still difficult. This should be taken into account when recommendations and further research is proposed.

7.4 CONCLUSION: MAIN RESEARCH QUESTION

The main research question that is formulated in chapter 1 was: **WHAT IS THE IMPACT OF LARGE SCALE TRUCK PLATOONING ON TRAFFIC MANAGEMENT ON THE A15 CORRIDOR?**

Platooning increases the traffic flow but decreases the traffic safety and efficiency within weaving, merging and diverging areas. This is especially the case when a mean and maximum intensity of platoons is on the road. Table 19 gives an overview of the overall results of the experiments.

Table 19: General overview of the results of the impact of large scale truck platooning within specific traffic locations

	Weaving			Merging			Diverging		
	Flow	*Efficiency*	*Safety*	*Flow*	*Efficiency*	*Safety*	*Flow*	*efficiency*	*Safety*
Minimum intensity	+	++	o	+	--	++	+	+	-
Mean intensity	+	-	--	+	--	--	+	o	--
Maximum intensity	+	--	--	+	--	-	+	--	--

* *- Impact* *o Impact is equal to base situation* *+ Positive*
-- Severe impact *++ Improving*

Weaving area: Platooning has an impact on the lane change behavior at the end of the weaving area. Low velocities of the vehicles are registered and this creates a moving bottleneck within the weaving area. Queue delay occurs for every traffic lane and it can be stated that this is increased by the difficulties that vehicles have when they need to perform a lane change. Additionally, within the weaving area merging of platoons to the desired lane is also influenced by platoons on the main road.

Merging area: Merging of vehicles is more difficult compared to the situation with single trucks on the road. Vehicles at the end of the merging lane need to decelerate or even stop to perform a lane change to the main road. This increases traffic conflicts at the end of the merging lane because vehicles perform a lane change with a low velocity.

Diverging area: Vehicles perform lane changes at the last possible moment due to platooning on the road. This increases traffic conflicts within this area. Additionally, there are many fluctuations in acceleration and deceleration behavior which is not beneficial for the traffic efficiency. When platoons drive on the deceleration lane it is almost impossible for cars to merge onto the adjacent lane. The fluctuations in efficiency also occur upfront the diverging area and this increases the queue delay.

Road traffic management strategies

According to the experiments executed in chapter 5, large scale platooning has an impact on the traffic management within complex traffic locations. The traffic flow within these areas is optimized but safety and efficiency is affected by platoons in a negative way. To enhance truck platooning, specific road strategies are proposed which might increase the safety and efficiency in weaving, merging and diverging locations of the A15 corridor. Two strategies can give an indication that it could enhance large scale truck platooning:

- Left lane driving of platoons (*Engineering*);
- Dynamic speed reductions (*Engineering*).

These two specific road strategies focusses on the engineering factor of traffic management. With these specific road strategies a framework is defined (Table 20). The road strategies should be focusing on the traffic safety and efficiency in relation to large scale truck platooning.

Table 20: An indication on which criteria the road strategies should be applied on

Intensity of platoons	Traffic flow	Efficiency	Safety	Road strategies
Minimum			x	*Inform other road users by road side units or send them a notification. Apply the road strategy based on the human factor*
Mean		x	x	*Decrease the difference in driving behavior by decreasing the overall velocity. Additionally, give information to human drivers*
Maximum		x	x	*Decrease the difference in driving behavior by adjusting overall traffic speed, give information to human drivers. Apply platooning partially outside the peak hours and test more with left side driving.*

These strategies are tested on an engineering level and more factors which are of influence should be included:

- *<u>Human factors</u>: human drivers safety, perception, truck drivers safety;*
- *<u>Environmental factors</u>: fuel reduction of platoons, emission of other road users due to platooning and the impact on the driving behavior.*

The proposed framework is a start to understand the influence of road traffic management strategies on the impact of large scale truck platooning.

7.5 EVALUATION IN CONTEXT

This research makes contribution to the understanding on which part of the traffic management truck platooning has an impact on. This research has provided insight which factors are important and are influenced by truck platooning. Platooning is in high development and it is predicted that it increases road capacity, throughput and safety. However, with large platooning this is not the case, safety and efficiency is decreased with a high intensity of platoons on the road. The results from the experiments can give more insight no what still needs to be done in order to successful implement truck platooning on the Dutch road infrastructure with a mixed type of vehicles.

The next steps are in cooperating more driving behavior characteristics of truck platooning. The platoons used in this study have a fixed distance of 6.7 meters. However, it is possible that when a non-platoon member enters the platoon because of dangerous driving behavior, platoon members adjust their distance within the safety margins. This can be an influence on the traffic performance within weaving, merging and diverging areas.

Additionally, realistic driving behavior and the human factors should be taken into account. Dangerous and compulsory driving behavior is not implemented in the simulation model VISSIM. Vehicles within the simulation model obey specific traffic rules which can be adjusted partially by the users. Not all parameters can be adjusted and this can result sometimes in unreal traffic behavior and does not represent real life driving behavior to its full extent. Human factors are important in relation to driving behavior. Stress, fatigue, dangerous driving behavior are not included in the simulation model. Human factors in relation to driving behavior can be understand by available literature but driving behavior per country and location can be different. The available literature discusses the interaction between trucks and cars but not platooning. Platooning is currently being tested on the road and from these studies the impact on the driving behavior and especially the impact on the psychological state of drivers needs to be analyzed to make further assumptions and predictions. Additionally, the traffic network that is constructed in VISSIM has no surrounding environment or fluctuations in height of the road (e.g. on and off ramp). These aspects can be important to fully understand the traffic performance on highways.

The results that are presented in chapter 5 on show marginal differences on traffic flow, jamming and safety. Therefore, the results should be considered as a prediction what would happen if platooning is applied on the road. Further analyses and tests should be done to fully understand the impact of platooning on the A15 corridor within these traffic situations.

BIBLIOGRAPHY

Al Alam, A., Gattami, A., & Johansson, K. (2010). An experimental study on the fuel reduction potential of heavy duty vehicle platooning. *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC* (pp. 306-311). Madeira Island, Portugal: IEEE.

Alam, A., Besselink, B., Turri, V., Martensson, J., & Johansson, K. (2015). Heavy-duty vehicle platooning for sustainable freight transportation: A cooperative method to enhance safety and efficiency. *IEEE Control Systems*, 34-56.

Alfraheed, M., Dröge, A., Klingender, M., Schilberg, D., & Jeschke, S. (2011). Longitudinal and lateral control in automated highway systems: Their past, present and future. In M. Alfraheed, A. Dröge, M. Klingender, D. Schilberg, & S. Jeschke, *Intelligent Robotics and Applications* (pp. 589-598). Berlin Heidelberg: Springer-Verlag.

Alian, S., Baker, R. G., & Wood, S. (2016). Rural casualty crashes on the Kings Highway: A new approach for road safety studies. *Accident Analysis and Prevention*, 8 - 19.

Alkim, T., Vliet, A. v., Aarts, L., & Eckhardt, J. (2016, June). *European Truck Platooning Challenge 2016 European Truck Platooning Challenge 2016 Hypothesis and recommendations for future.* Opgeroepen op September 5, 2016, van www.eutruckplatoonchallenge.com: https://www.eutruckplatooning.com/Support/Booklet+Lessons+Learnt/handlerdownloadfiles.ashx?idnv=529927

Anderson, A. J. (1989). Chapter 11: Association between variables. In A. J. Anderson, *Interpreting data: a first course in statistics* (pp. 767 - 786). Boca Raton, Florida: Chapman and Hall/CRC Press.

Angelidou, M. (47 (2015)). Smart cities: a conjuncture of four forces. *Cities*, 95 - 106.

ANWB. (2016, October 21). *Verkeer: Dagelijkse drukke trajecten ochtend en avondspits*. Opgehaald van www.anwb.nl: http://www.anwb.nl/verkeer/nederland/verkeersinformatie/dagelijkse-drukke-trajecten

Arem, B. v., Cornelie, J. G., & Visser, R. (2006). The Impact of Cooperative Adaptive Cruise Control on Traffic Flow Characteristics. *IEEE Transactions on Intelligent Transportation Systems 7*, 429 -436.

Barcelo, J. (2010). Chapter 1: Models, Traffic Models, Simulation, and Traffic Simulation. In J. Barceló, *Fundamentals of Traffic Simulation* (pp. 1 - 62). New York: Springer Science+Business Media.

Barcelo, J., Codina, E., Casas, J., Ferrer, J., & Garcia, D. (2004). Microscopic Traffic Simulation : A Tool for the Design , Analysis and Evaluation of Intelligent Transport Systems. *Journal of Intelligent and Robotic Systems*, 173 - 203.

Bergenhem, C., Hedin, E., & Skarin, D. (2012). Vehicle-to-Vehicle Communication for a Platooning System. *Procedia - Social and Behavioral Sciences*, 1222 - 1233.

Bettencourt, L. M., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth innovation, scaling, and the pace of life in cities. *PNAS 104*, 7301 - 7306.

Brügmann, J., Schreckenberg, M., & Luther, W. (2014). A verifiable simulation model for real-world microscopic traffic simulations. *Simulation Modelling Practice and Theory*, 58-92.

Bruijel, K. (2016, July 14). *Mobiliteit: Verkeersmanagement verandert voor zelfrijdende auto's*. Opgehaald van De techniek achter Nederland: http://www.detechniekachternederland.nl/mobiliteit/infratechniek-verkeer/verkeersmanagement-verandert-voor-zelfrijdende-autos/

Burnett, G., & Diels, C. (2014). Driver Acceptance of In-Vehicle Information, Assistance and Automated Systems: An Overview. In M. A. Regan, T. Horberry, & A. Stevens, *Driver Acceptance of New Technology: Theory, Measurement and Optimisation* (pp. 137 - 148). Surrey, England: Ashgate Publishing LImited.

Casas, J., Ferrer, J. L., Garcia, D., Perarnau, J., & Torday, A. (2010). Traffic Simulation with Aimsum. In J. Barceló, *Fundamentals of Traffic Simulation* (pp. 173 - 232). New York: Springer Science+Business Media.

CBS. (2017, March 21). *Aantal verkeersdoden stijgt naar 621 in 2015*. Opgehaald van www.cbs.nl: https://www.cbs.nl/nl-nl/nieuws/2016/16/aantal-verkeersdoden-stijgt-naar-621-in-2015

Centraal Bureau voor Statistiek. (2016, November 11). *Transport en Mobiliteit 2015.* Opgehaald van www.cbs.nl: http://download.cbs.nl/pdf/2015-transport-en-mobiliteit-2015.pdf

Chan, E., Gilhead, P., Jelínek, P., Krejčí, P., & Robinson, T. (2012). Cooperative control of SARTRE automated platoon vehicles. *Proceedings of the 19th ITS World Conference* (pp. 1-9). Vienne, Austria: ITS World Congress.

Coifman, B., Wu, M., Redmill, K., & Thornton, D. A. (2016). Collecting ambient vehicle trajectories from an instrumented probe vehicle. *Transportation Research Part C: Emerging Technologies*, 254 - 271.

Curtis, K., & Youngquist, S. T. (2013 (32)). Part 21: Categoric analysis: Pearson chi-square test. *Air Medical Journal*, 179 - 180.

Dijkstra, A. (2013). Assessing the safety of routes in a regional network. *Transportation Research Part C: Emerging Technologies*, 103 - 115.

Dodemont, B. (2016, October 11). EU truck platoon Challenge and the Port of Rotterdam. (A. Kuijpers, Interviewer)

Durrani, U., Lee, C., & Maoh, H. (2016). Calibrating the Wiedemann's vehicle-following model using mixed vehicle-pair interactions. *Transportation Research Part C: Emerging Technologies*, 227 - 242.

Eriksson, A., & Stanton, N. A. (2017). Takeover Time in Highly Automated Vehicles: Nnoncritical Transitions to and From Manual Control. *Human Factors The Journal of the Human Factors and Ergonomics Society*.

ERTRAC. (2015). *Automated Driving Roadmap.* Opgeroepen op September 13, 2016, van www.Ertrac.org: http://www.ertrac.org/uploads/documentsearch/id38/ERTRAC_Automated-Driving-2015.pdf

European Truck Platooning . (2016, July 26). *European Truck Platooning Challenge*. Opgehaald van www.eutruckplatooning.com: https://www.eutruckplatooning.com/default.aspx

European Truck Platooning. (2016, March 30). *Truck Platooning: Safety First*. Opgeroepen op September 17, 2016, van https://www.eutruckplatooning.com/News/485681.aspx?t=Truck+platooning%3A+safety+first

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles : opportunities, barriers and policy recomemendation. *Transport Research Part A 77*, 167 - 181.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, 167-181.

Fan, R., Wang, W., Liu, P., & Yu, H. (2013). Using VISSIM simulation model and Surrogate Safety Assessment Model for estimating field measured traffic conflicts at freeway merge areas. *IET Intelligent Transport Systems*, 68 - 77.

Fellendorf, M., & Vortisch, P. (2010). Microscopic Traffic Flow Simulator VISSIM. In J. Barceló, *Fundamentals of Traffic Simulation* (pp. 63 - 93). New York: Springer-Verlag.

Ferrari, P. (2009). The effect of the competition between cars and trucks on the evolution of the motorway transport system. *Transportation Research Part C: Emerging Technologies*, 558 - 570.

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis and Prevention*, 461 - 472.

Gao, Y. (2008). *Calibration and comparison of the VISSIM and Integration Microscopic Traffic Simulation Model.* Blacksburg: Vriginia Polytechnic Institute and State University.

Garau, C., Masala, F., & Pinna, F. (2016). Cagliari and smart urban mobility: Analysis and comparison. *Cities 56*, 35 - 46.

Gettman, D., & Head, L. (2003). Surrogate Safety Measures from Traffic Simulation Models. *Transportation Research Record*, 104- 115.

Gleave, S. D., Frisoni, R., Dall'Oglio, A., Nelson, C., Long, J., Vollath, C., . . . Mcminimy, S. (2016, July 27). *Supporting analysis: Research for TRAN Committee - Self-piloted cars: the future of road transport.* Opgehaald van Europe parlement: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/573434/IPOL_STU(2016)573434_EN.pdf

Goh, K., Currie, G., Sarvi, M., & Logan, D. (2013). Exploring Bus Lane Safety Impacts Using Traffic Microsimulation. *Australasian Transport Research Forum 2013 Proceedings* (pp. 1 - 17`). Brisbane, Australia: http://www.patrec.org/atrf.aspx.

Golob, T. F., Recker, W. W., & Alvarez, V. M. (2004). Safety aspects of freeway weaving sections. *Transportation Research Part A: Policy and Practice*, 35-51.

Gora, P., & Rüb, I. (2016). Traffic Models for Self-driving Connected Cars. *Transportation Research Procedia*, 2207 - 2216.

Guériau, M., Billot, R., El Faouzi, N., Monteil, J., Armetta, F., & Hassas, S. (2016). How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies. *Transportation Research Part C: Emerging Technologies*, 266-279.

Heijden, R. v. (2016, July 27). *Achtergrond: "Snel zelfrijdende voertuigen op de weg is een illusie"*. Opgehaald van kennislink: http://www.kennislink.nl/publicaties/snel-zelfrijdende-voertuigen-op-de-weg-is-een-illusie

Heywood, J. B. (2010). Assessing the fuel consumption and GHG of future in-use vehicles. *Energy and Sustainable Development: Issues and strategies (ESD)*, 1-12.

Higgs, B., Abbas, M., & Medina, A. (2011). Anlysis of the Wiedemann Car Following Model over Different Speeds using Naturalistic Data. *3th Internation Conference on Road Safety and Simulation*, (pp. 1 - 22). Indianapolis, Indiana.

Hollands, R. (2008). Will the real smart city please stand up? *City 12:3*, 303 - 318.

Hoogendoorn, R. G., van Arem, B., & Hoogendoorn, S. P. (2012). A neurofuzzy approach to modeling longitudinal driving behavior and driving task complexity. *International Journal of Vehicular Technology*, 1-12.

Hoogendoorn, S., Taale, H., Wilmink, I., Bertini, R. L., Katwijk, R. v., Immers, B., & Schuurman, H. (2012). *The future of traffic management: State of the Art, Current Trends and Perspectives for the future.* Delft: TrafficQuest.

Hottentot, C. (2017, January 10). Truck platooning. (A. Kuijpers, Interviewer)

Howell, D. (2016, November 7). *Chi-square test - Analysis of Contigency tables.* Opgehaald van www.uvm.edu: https://www.uvm.edu/~dhowell/methods7/Supplements/ChiSquareTests.pdf

Huang, F., Liu, P., Yu, H., & Wang, W. (2013). Identifying if VISSIM simulation model and SSAM provide reasonable estimates for field measured traffic conflicts at signalized intersections. *Accident Analysis and Prevention*, 1014 - 1024.

Jak, M. (2016, August 16). Research focus of truck platooning in the Port of Rotterdam. (A. Kuijpers, Interviewer)

Janssen, R., Zwijnenberg, H., Blankers, I., & Kruijf, J. d. (2016, August 18). *Nieuws: truck platooning: driving the future of transportation - TNO whitepaper.* Retrieved from www.tno.nl: https://www.tno.nl/en/about-tno/news/2015/3/truck-platooning-driving-the-future-of-transportation-tno-whitepaper/

Jongenotter, I. E. (2016, Septemeber 15). Possible adjustments infrastructure in order to support truck platooning. (A. Kuijpers, Interviewer)

Khodayari, A., Ghaffari, A., Ameli, S., & Flahatgar, J. (2010). A historical review on lateral and longitudinal control of autonomous vehicle motions. *ICMET 2010 - 2010 International Conference on Mechanical and Electrical Technology, Proceedings*, 421 - 429.

KNMI. (2016, November 11). *Winter 2014-2015 (december, januari, februari)*. Opgehaald van www.knmi.nl: https://www.knmi.nl/nederland-nu/klimatologie/maand-en-seizoensoverzichten/2015/winter

Kuwahara, M., Horiguchi, R., & Hanabusa, H. (2010). Chapter 3: Traffic Simulation with AVENUE. In J. Barceló, *Fundamentals of traffic simulation* (pp. 399 - 430). New York: Springer Science+Business Media.

Laerd Statistics. (2016, November 4). *Chi-Square Goodness-of-fit Test in SPSS Statistics*. Opgehaald van Laerd Statistics: https://statistics.laerd.com/spss-tutorials/chi-square-goodness-of-fit-test-in-spss-statistics.php

Larsson, E., Sennton, G., & Larson, J. (2015). The vehicle platooning problem: Computational complexity and heuristics. *Transportation Research Part C: Emerging Technologies*, 258 - 277.

Laval, J., & Daganzo, C. (2006). Lane-changing in traffic streams. *Transportation Research Part B: Methodological*, 251 - 264.

Li, X., & Sun, J. Q. (2017). Studies of vehicle lane-changing dynamics and its effect on traffic efficiency, safety and environmental impact. *Physica A: Statistical Mechanics and its Applications*, 41-58.

Lighthill, M. J., & Whitham, G. B. (1955). On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 317 - 345.

Liu, L., Li, X., & Jia, B. (2014). Traffic Dynamics Around Weaving Section with Mixed Slow and Fast Vehicles based on Cellular Automata Model. *Procedia - Social and Behavioral Sciences*, 548-556.

Lockwood, R. (2016, April). *Truck Platooning, Past, Present and Future*. Opgeroepen op September 15, 2016, van http://www.truckinginfo.com/article/story/2016/04/platooning-is-on-the-way.aspx

Marczak, F., Daamen, W., & Buisson, C. (2013). Key Variables of Merging Behaviour: Empirical Comparison Between Two Sites and Assessment of Gap Acceptance Theory. *Procedia Social and Behavioral Sciences*, 678 - 697.

Martens, J., & Beenakker, M. (2017, January 04). DAF Trucks and Truck Platooning. (A. Kuijpers, Interviewer)

Martens, J., & Beenakkers, M. (2017, January 04). Truck platooning. (A. Kuijpers, Interviewer)

Martínez, M. P., Garcia, A., & Moreno, A. (2011). Traffic microsimulation study to evaluate freeway exit ramps capacity. *Procedia - Social and Behavioral Sciences*, 139 - 150.

McHugh, M. L. (2013). The Chi-square test of independence. *Biochemia Medica*, 143 - 149.

Metropoolregio Rotterdam Den Haag. (2017, March 6). *nieuws: Vracht- en bestelverkeer gespot*. Opgehaald van www.mrdh.nl: http://mrdh.nl/nieuws/vracht-en-bestelverkeer-gespot

Michalaki, P., Quddus, M., Pitfield, D., & Huetson, A. (2016). A time-series analysis of motorway collisions in England considering road infrastructure, socio-demographics, traffic and weather characteristics. *Journal of Transport and Health*, 9 - 20.

Michon, J. A. (1985). A critical view of driver behavior models: what do we know, what should we do? *Human Behavior and traffic safety*, 485 - 520.

Ministerie van infrastructuur en milieu. (2015, January 23). *Kamerstuk; 31 305 Mobiliteitsbeleid*. Opgehaald van www.overheid.nl: https://zoek.officielebekendmakingen.nl/dossier/31305/kst-31305-212?resultIndex=8&sorttype=1&sortorder=4

Ministerie van Infrastructuur en Milieu. (2015, March 02). *Richtlijn Ontwerp Autosnelwegen 2014.* Opgehaald van www.rijkswaterstaat.nl:

https://staticresources.rijkswaterstaat.nl/binaries/Richtlijn%20Ontwerp%20Autosnelwegen%202014_tcm21-76103.pdf

Naiem, A., Reda, M., El-Beltagy, M., & El-Khodary, I. (2010). An Agent Based Approach for Modeling Traffic Flow. *Conference on Informatics and Systems (INFOS), 2010 The 7th International*, 1 - 6.

Nowakowski, C., Shladover, S. E., & Tan, H. (2015). Heavy vehicle automation : Human factors lessons learned. *Procedia Manufacturing*, 2495-2952.

Ossen, S., & Hoogendoorn, S. P. (2011). Heterogeneity in car-following behavior: Theory and empirics. *Transportation Research Part C: Emerging Technologies*, 182 - 195.

Oud, M. (2016). *Master Thesis: Performance of Existing Integrated Car Following and Lane Chane Models around Motorway ramps.*

Owens, J. M., Antin, J. F., Doerzaph, Z., & Willis, S. (2015). Cross-generational acceptance of and interest in advanced vehicle technologies: A nationwide survey. *Transportation Research Part F*, 139 - 151.

Özgüner, Ü., Stiller, C., & Redmill, K. (2007). Systems for safety and autonomous behavior in cars: The DARPA grand challenge experience. *Proceedings of the IEEE*, 397 - 412.

Papageorgiou, G. N. (2006). Towards a microscopic simulation model for traffic management: A computer-based approach. *11th {IFAC} Symposium on Control in Transportation Systems*, (pp. 403 -411).

Papathanasopoulou, V., Markou, I., & Antoniou, C. (2016). Online calibration for microscopic traffic simulation and dynamic multi-step prediction of traffic speed. *Transportation Research Part C: Emerging Technologies*, 144 - 159.

Pauzie, A., & Orfila, O. (2016). Methodologies to assess usability and safety of ADAS and automated vehicle. *IFAC-PapersOnLine*, 72-77.

Peeta, S., Zhang, P., & Zhou, W. (2005). Behavior-based analysis of freeway car-truck interactions and related mitigation strategies. *Transportation Research Part B: Methodological*, 417 - 451.

Pillath, S. (2016, January 7). *Automated vehicles in the EU.* Opgehaald van European Parlement Think Tank: http://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_BRI(2016)573902

Ploeg, J. (2014). *Analysis and design of controllers for cooperative and automated driving.* Eindhoven: Technische Universiteit Eindhoven.

Port of Rotterdam. (2015, September 21). *Havenvisie 2030* . Opgehaald van Port of Rotterdam: https://www.portofrotterdam.com/nl/de-haven/havenvisie-2030

Port of Rotterdam. (2016, June). *Havenkrant editie 30: ze komen eraan zelfrijdende vrachtwagens*. Opgehaald van Port of Rotterdam: https://www.joomag.com/magazine/havenkrant-2-2016/0737940001465372175?short

Port of Rotterdam. (2016, June 14). *Wegtransport*. Opgehaald van www.portofrotterdam.com: https://www.portofrotterdam.com/nl/verbindingen-logistiek/intermodaal-transport/wegtransport

ptv. (2011). *VISSIM Manual 5.30 - 05 User Manual.*

Ram, T., & Chand, K. (2016). Effect of drivers' risk perception and perception of driving tasks on road safety attitude. *Transportation Research Part F: Traffic Psychology and Behaviour*, 1-15.

Ran, B., Leight, S., & Chang, B. (1999). A microscopic simulation model for merging control on a dedicated-lane automated highway system. *Transportation Research Part C: Emerging Technologies*, 369-388.

RDW. (2012). *Ontheffingen: overzicht maten en gewichten in Nederland.* Opgehaald van www.rwd.nl: http://www.rdw.nl/SiteCollectionDocuments/Ontheffingen (TET)/Themasite Ontheffingen/Handleidingen/2 B 1097b Overzicht maten en gewichten.pdf

Rijksoverheid. (2008). *Strategisch Plan Verkeersveiligheid.* Opgeroepen op September 19, 2016, van www.rijksoverheid.nl: https://www.rijksoverheid.nl/onderwerpen/verkeersveiligheid/documenten/beleidsnota-s/2009/06/15/strategisch-plan-verkeersveiligheid-2008-2020

Rijkswaterstaat. (2016, November 29). *Richtlijn Ontwerp Autosnelwegen.* Opgehaald van www.rijkswaterstaat.nl: https://staticresources.rijkswaterstaat.nl/binaries/Richtlijn%20Ontwerp%20Autosnelwegen%202014_tcm21-76103.pdf

Sadayuki, T. (2013). An Overview on an Automated Truck Platoon within the Energy ITS Project. *7th IFAC Symposium on Advances in Automotive Control* (pp. 41-46). Tokyo, Japan: The International Federation of Automatic Control.

SAE On-Road Automated Vehicle Standards Committee. (2014, January). *SAE Standard J3016: Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems.* Opgeroepen op September 5, 2016, van www.sae.org: http://www.sae.org/misc/pdfs/automated_driving.pdf

Sia Partners. (2016, June). *Platooning Towards Sustainable Road Freight Transport.* Opgeroepen op September 19, 2016, van Sia partners: http://transport.sia-partners.com/sites/default/files/insight_platooning_-_benefits_drawbacks_and_future_outlook.pdf

Soriguera, F., Martínez, I., Sala, M., & Menéndez, M. (2017). Effects of low speed limits on freeway traffic flow. *Transportation Research Part C: Emerging Technologies*, 257 - 274.

Sugimachi, T., Fukao, Y., Suzuki, Y., & Kawashima, H. (2013). Development of autonomous platooning system for heavy-duty trucks. *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 52-57.

Summala, H. (1996). Accident risk and driver behaviour. *Safety Science*, 103 117.

SWOV Institute for road safety research. (2017, January 11). *SWOV Fact Sheet: Headway times and road safety.* Opgehaald van www.swov.nl: https://www.swov.nl/sites/default/files/publicaties/gearchiveerde-factsheet/uk/fs_headway_archived.pdf

Sykes, P. (2010). Chapter 4 Traffic Simulation with Paramics. In J. Barceló, *Fundamentals of Traffic Simulation* (pp. 131 - 171). New York: Springer Science+Business Media.

Trantow, S., Stieger, S., Hees, F., & Jescke, S. (2013). Automation, Communication and Cybernetics in Science and Engineering 2011/2012. *Automation, Communication and Cybernetics in Science and Engineering 2011/2012*, 437 - 444.

Tsugawa, S., Kato, S., & Aoki, K. (2011). An automated truck platoon for energy saving. *IEEE International Conference on Intelligent Robots and Systems*, 4109 - 4114.

United Nations. (2014). *Publications: World Urbanization Prospects.* Opgehaald van United Nations: https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf

Verlaan, J. G., & Schoenmaker, R. (2013). Infrastructure Management: dynamic control of assets. *IPWEA 2013: Biennial Conference of the Institute of Public Works Engineering Australasia* (pp. 1-9). Darwin, Australia: Institutional Repository.

Wegman, F. (2016). The future of road safety: A worldwide perspective. *IATSS Research*, 66 - 71.

Wei, J., Dolan, J., & Litkouhi, B. (2013). Autonomous vehicle social behavior for highway entrance ramp management. *IEEE Intelligent Vehicles Symposium, Proceeding*, 201 - 207.

Witteveen+Bos. (2016, December 2). Brainstorm session smart mobility. Deventer.

Witteveen+Bos Raadgevende Ingenieurs B.V. (2016). *Analys Weigh in Motion en beladingsgraadscanner.* Deventer: Witteveen+Bos.

Xun, S., Tomio, M., & Takayuki, M. (2011 11(3)). The Impact of Automated Truck Lanes on Intercity Expressways: A Study Using Hybrid Simulator. *Journal of Transportation Systems Engineering and Information Technology*, 32-42.

Young, W., Sobhani, A., & Lenné, M. G. (2014). Simulation of safety: A review of the state of the art in road safety simulation modelling. *Accident Analysis and Prevention*, 89 - 103.

Zheng, K., Zheng, Q., Yang, H., Zhao, L., Hou, L., & Chatzimisios, P. (2015). Reliable and Efficient Autonomous Driving: The Need for Heterogeneous Vehicular Networks. *IEEE Communications Magazine vol. 53 Issue:12*, 72 - 79.

APPENDIX

LIST OF FIGURES

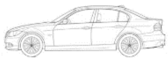
LIST OF TABLES

A1. VEHICLE CATEGORIES

Various vehicles are detected in the traffic data of the A15 corridor (RDW, 2012).

1. Vehicle category 1

Length	12	meter
Width	2,55	meter
Height	4	meter



2. Vehicle category 2:

Length	12	meter
Width	2,55	meter
Height	4	meter

3. Vehicle category 3

Combination truck with semitrailer

Length	16.50	meter
Width	2,55	meter
Height	4	meter
Maximum weight	50.000	kg

Combination truck with trailer

Length	18.75	meter
Width	2,55	meter
Height	4	meter
Maximum weight	50.000	kg

A2. DATA PREPARATION: HOLIDAYS

The dates 25-12-2015 and 26-12-2015 are not taken into account in the analysis. These days in the data set had error values and therefore these holidays are not taken into account in the analysis.

Table A 1: Holidays in the year 2015

Date	Day	Holiday type
1-1-2015	Thursday	New Year's day
3-4-2015	Friday	Good Friday
5-4-2015	Sunday	Eastern
6-4-2015	Monday	Eastern
27-4-2015	Monday	Kings day
5-5-2015	Tuesday	Liberation day
14-5-2015	Thursday	Ascension day
24-5-2015	Sunday	Pentecost
25-5-2015	Monday	Pentecost
27-7-2015 / 14-8-2015	-	Holidays center of the Netherlands ('Bouwvak')
25-12-2015	Friday	Christmas
26-12-2015	Saturday	Christmas

A3. DESCRIPTIVE ANALYSIS

The outcomes on the mean, standard deviation and variance of every group are calculated in SPSS. The descriptive analysis is executed with the Chi-square test and the Cramer's V.

A3.1 GROUP 1: SEASONS

Outcomes of the descriptive analysis of group 1.

Table A 2: Amount of cases in the analysis

Group 1	Winter	'spring'	Summer
N VelocityCat01	80659	142283	117941
N VelocityCat03	54060	97380	84584
N IntensityCat01	83382	142033	117320
N IntensityCat03	53382	97130	83963

Table A 3: Outcomes of the mean, standard deviation and variance during different seasons

Group 1	Mean Velocity		Mean Intensity		Std. Deviation Velocity		Std. Deviation Intensity		Variance Velocity		Variance intensity	
	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3
Winter	95,47	79,19	1694,61	230,77	16,344	13,136	1302,185	272,639	267,119	172,543	1,69*10^6	7,43*10^4
'Spring'	93,53	79,21	1383,59	232,28	16,443	13,064	1047,356	270,159	270,364	170,656	1,09*10^6	7,29*10^4
Summer	91,80	79,42	1270,40	232,44	16,718	13,526	1011,347	266,007	279,494	182,946	1,02*10^5	7,08*10^4

A3.1.1 GROUP 1: SIGNIFICANCE TEST OF THE SEASONS

A significance test is executed over the velocity and intensity of the two vehicle categories. The Chi-square test is used to test the significance. Section 4.5 of chapter 4, a short elaboration is given on this method. Table A3.1.1 gives an example of a significant test that is executed in SPSS. The velocity of vehicle category 1 is tested between the winter period and the remaining seasons.

Table A 4: Significance test over the velocity and intensity

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VelocityWinterCat01*VelocityRemainingSeasonsCat01	78306	52,8%	70014	47,2	148320	100%

Table A 5: Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	57811,866*	24806	,000
Likelihood Ratio	24526,141	24806	0,896
Linear-byy-linear Association	6243,937	1	,000
N of Valid Cases	78306		

** 22795 cells (90,7%) have expected count less than 5. The minimum expected count is ,00*

Table A 6: CRAMER'S V TEST

		Value	Approximate Significance
Nominal by Nominal	Phi	0,859	,000
	Cramer's V	,069	,000
N valid Cases		78306	

A3.2. GROUP 2: HOLIDAYS AND NON HOLIDAYS

Outcomes of the descriptive analysis of group 2.

Table A 7: Amount of cases in the analysis

Group 2	Holidays	Non-holidays
N VelocityCat01	40111	302204
N VelocityCat03	24488	211035
N IntensityCat01	41681	321631
N IntensityCat03	41681	321631

Table A 8: Outcomes of the mean, standard deviation and variance during holidays and non-holidays

	Mean Velocity		Mean Intensity		Std. Deviation Velocity		Std. Deviation Intensity		Variance Velocity		Variance intensity	
	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3
Holidays	96,11	79,69	1151,21	178,41	14,493	15,774	810,189	236,490	210,055	248,821	6,56*10^5	5,59*10^5
Non-holidays	93,06	79,07	1447,95	272,005	16,866	13,399	1139,913	272,005	284,467	179,520	1,29*10^6	7,39*10^4

A3.3. GROUP 3: WEEKDAYS AND WEEKENDS

Outcomes of the descriptive analysis of group 3.

Table A 9: Amount of cases in the analysis

Group 3	Weekdays	Weekend
N VelocityCat01	234401	96615
N VelocityCat03	200446	30761
N IntensityCat01	248306	103485
N IntensityCat03	248306	103485

Table A 10: Outcomes of the mean, standard deviation and variance during weekdays and weekends

Group 3	Mean Velocity		Mean Intensity		Std. Deviation Velocity		Std. Deviation Intensity		Variance Velocity		Variance intensity	
	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3
Weekday	90,26	78,48	1523,38	323,44	17,969	13,745	1192,131	277,255	322,873	188,919	1,42*10^6	7,69*10^4
Weekend	100,29	83,79	1176,31	32,04	9,965	8,720	861,717	68,258	99,291	76,046	7,43*10^5	4659,156

A3.4. GROUP 4: PEAK AND OFF PEAK HOURS

The standard deviation during peak and off peak hours of group 4.

Table A 11: Standard deviation velocity and intensity during peak and off peak hours within the different seasons

Group 4	Std. Deviation velocity Peak hours 06:30 - 09:30		Std. Deviation intensity Peak hours 06:30 - 09:30		Std. Deviation velocity Peak hours 15:30 - 19:00		Std. Deviation intensity Peak hours 15:30 - 19:00		Std. Deviation velocity Off peak hours 09:31 - 15:29		Std. Deviation intensity Off peak hours 09:31 - 15:29	
	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3
Winter	17,676	13,913	1017,620	176,125	24,602	20,000	931,049	195,663	8,278	6,372	692,152	219,817
'Spring'	19,451	15,667	1151,840	181,672	23,257	19,316	981,940	195,044	8,288	6,392	732,516	204,679
Summer	17,125	13,667	974,656	180,625	21,673	17,897	1025,108	195,548	11.597	9,634	747,802	201,682
	Std. Deviation velocity Peak hours 19:01 - 00:00		Std. Deviation intensity Peak hours 19:01 - 23:59		Std. Deviation velocity Peak hours 00:00 - 06:29		Std. Deviation intensity Peak hours 00:00 - 06:29					
	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3	Cat1	Cat3				
Winter	7,895	6,616	509,832	113,867	13,891	9,088	1155,392	1339,606				
'Spring'	11,313	7,059	490,853	125,100	15,785	9,476	937,931	142,285				
Summer	17,426	13,624	510,427	113,302	19,094	14,929	830,914	138,261				

A4. SIGNIFICANCE TEST: CHI-SQUARE

A significance test is executed over the velocity and intensity of the two vehicle categories of every group. The Chi-square test is used to test the significance. Section 4.5 gives a short elaboration on this method. The outcomes of the Chi-square test of group 1 are given as an example.

A4.1 GROUP 1

With the Chi-square test and the Cramer's V test a significance test can be executed. The velocity and intensity of the two vehicle categories is tested on significance. In most cases the Chi-square test was not sufficient and therefore a Cramer's V is executed to define when there is a significance the significance is strong or weak.

Table A 12: Velocity category 1 significance test between winter and remaining seasons

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VelocityWinterCat01*VelocityRemainingSeasonCat01	7220	99,7%	20	0,3%	7240	100%

Table A 13: Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	57811,866*	24806	,000
Likelihood Ratio	24526,141	24806	0,896
Linear-byy-linear Association	6243,937	1	,000
N of Valid Cases	78306		

** 22795 cells (90,7%) have expected count less than 5. The minimum expected count is ,00*

Table A 14: Symmetric measures

		Value	Approximate Significance
Nominal by Nominal	Phi	0,859	,000
	Cramer's V	,069	,000
N valid Cases		78306	

Table A 15: Velocity category 1 significance test between winter and summer

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VelocityWinterCat01*VelocitySummerCat01	71291	48,1%	77029	51,9%	148320	100%

Table A 16: Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	57397,389*	24024	,000
Likelihood Ratio	18104,370	24024	1,000
Linear-byy-linear Association	272,675	1	,000
N of Valid Cases	71291		

** 22218 cells (91,3%) have expected count less than 5. The minimum expected count is ,00*

Table A 17: Symmetric measures

		Value	Approximate Significance
Nominal by Nominal	Phi	0,897	,000
	Cramer's V	,072	,000
N valid Cases		71291	

Table A 18: Velocity category 1 significance test between remaining season and summer

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
VelocityRemainingSeasonCat01*VelocitySummerCat01	115054	77,6%	33266	22,4%	148320	100%

Table A 19: Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	69351,645*	26076	,000
Likelihood Ratio	27411,967	26076	,000
Linear-byy-linear Association	2720,190	1	,000
N of Valid Cases	115054		

** 23432 cells (88,8%) have expected count less than 5. The minimum expected count is ,00*

Table A 20: Symmetric measures

		Value	Approximate Significance
Nominal by Nominal	Phi	0,776	,000
	Cramer's V	,062	,000
N valid Cases		115054	

Table A 21: Intensity category 1 significance test between winter and remaining season

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
IntensityWinterCat01*IntensityRemainingSeasonsCat01	83212	56,1%	65108	43,9%	148320	100%

Table A 22:Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	107842,049*	11448	,000
Likelihood Ratio	79760,260	11448	,000
Linear-byy-linear Association	28071,728	1	,000
N of Valid Cases	83212		

** 7327 cells (62,8%) have expected count less than 5. The minimum expected count is ,00*

Table A 23: Symmetric measures

		Value	Approximate Significance
Nominal by Nominal	Phi	1,138	,000
	Cramer's V	,111	,000
N valid Cases		83212	

Table A 24: Intensity category 1 significance test between winter and summer

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
IntensityWinterCat01*IntensitySummerCat01	82850	55,9%	65470	44,1%	148320	100%

Table A 25: Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	72776,409*	11024	,000
Likelihood Ratio	61317,557	11024	,000
Linear-byy-linear Association	21543,052	1	,000
N of Valid Cases	82850		

** 7354 cells (65,5%) have expected count less than 5. The minimum expected count is ,00*

Table A 26: Symmetric measures

		Value	Approximate Significance
Nominal by Nominal	Phi	0,937	,000
	Cramer's V	,092	,000
N valid Cases		82850	

Table A 27: Intensity category 1 significance test between remaining seasons and summer

	Cases					
	Valid		Missing		Total	
	N	Percent	N	Percent	N	Percent
IntensityRemainingSeasonCat01*IntensitySummerCat01	130231	87,8%	18089	12,2%	148320	100%

Table A 28: Chi-square test

	Value	df	Asymptotic Significance (2-sided)
Pearson Chi-square	150930,029*	11232	,000
Likelihood Ratio	108982,044	11232	,000
Linear-byy-linear Association	48349,943	1	,000
N of Valid Cases	130231		

** 7667 cells (67,0%) have expected count less than 5. The minimum expected count is ,00*

Table A 29: Symmetric measures

		Value	Approximate Significance
Nominal by Nominal	Phi	1,077	,000
	Cramer's V	,106	,000
N valid Cases		130231	

A5. SIMULATION SCENARIOS

The mean velocity and intensity of both vehicle categories do not differ significantly in the three seasons. Therefore, the mean is generalized and an overall mean is calculated (Table A 30).

Table A 30: Mean velocity and intensity of both vehicle categories of the three scenarios

	Scenario 1: Peak hour 1 (06:30 - 09:30)		Scenario 2: Peak hour 2 (15:30 - 19:00)		Scenario 3: Off peak hour (09:31 - 15:29)	
	Velocity	Intensity	Velocity	Intensity	Velocity	Intensity
Vehicle category 1	83,70	2632,6	74,73	2781,26	91,32	1779,85
Vehicle category 3	75,13	449,47	67,87	424,69	81,79	619,56

Table A 31: Mean standard deviation of the velocity and intensity of both vehicle categories of the three scenarios

	Scenario 1: Peak hour 1 (06:30 - 09:30)		Scenario 2: Peak hour 2 (15:30 - 19:00)		Scenario 3: Off peak hour (09:31 - 15:29)	
	Standard Deviation Velocity	Standard Deviation Intensity	Standard Deviation Velocity	Standard Deviation Intensity	Standard Deviation Velocity	Standard Deviation Intensity
Vehicle category 1	18,084	1048,039	23,177	979,366	9,388	724,157
Vehicle category 3	14,416	179,474	19,071	195,418	7,466	208,726

The standard deviations are used to determine the minimum and maximum velocity and intensity of these scenarios.

Table A 32: Minimum velocity and intensity of both vehicle categories of the three scenarios

	Scenario 1: Peak hour 1 (06:30 - 09:30)		Scenario 2: Peak hour 2 (15:30 - 19:00)		Scenario 3: Off peak hour (09:31 - 15:29)	
	Minimum Velocity	Minimum Intensity	Minimum Velocity	Minimum Intensity	Minimum Velocity	Minimum Intensity
Vehicle category 1	65,616	1584,561	51,553	1801,894	81,932	1055,693
Vehicle category 3	60,714	269,996	48,799	229,272	74,324	410,834

Table A 33: Maximum velocity and intensity of both vehicle categories of the three scenarios

	Scenario 1: Peak hour 1 (06:30 - 09:30)		Scenario 2: Peak hour 2 (15:30 - 19:00)		Scenario 3: Off peak hour (09:31 - 15:29)	
	Maximum Velocity	Maximum Intensity	Maximum Velocity	Maximum Intensity	Maximum Velocity	Maximum Intensity
Vehicle category 1	101,784	3680,639	97,907	3760,626	100,708	2504,007
Vehicle category 3	89,546	628,944	86,941	620,108	89,256	828,286

B1. INPUT VARIABLES FOR THE SIMULATION EXPERIMENTS

As explained in section 5.2, three scenarios are set up to test the impact of truck platooning on the three defined criteria. Each scenario has a base scenario which represent the traffic network on the A15 corridor with trucks and cars. Within the other three scenarios platoons are applied on the road instead of trucks.

Table B 1: Input variables for the three scenarios each with different intensities of platoons. These variables are used for case area 1 and case area 2

Scenario 1: Morning peak hour	Base scenario 1	Scenario 1.1 Minimum	Scenario 1.2 Mean	Scenario 1.3 Maximum
Intensity Cars	2633	2633	2633	2633
Intensity Trucks	450	--	--	--
Intensity Platoons	--	90	150	210
Scenario 2: Off peak hour (daytime)	Base scenario 2	Scenario 2.1 Minimum	Scenario 2.2 Mean	Scenario 2.3 Maximum
Intensity Cars	1780	1780	1780	1780
Intensity Trucks	411			
Intensity Platoons	--	137	206	276
Scenario 3: Afternoon peak hour	Base scenario	Scenario 3.1 Minimum	Scenario 3.2 Mean	Scenario 3.3 Maximum
Intensity Cars	2782	2782	2782	2782
Intensity Trucks	230			
Intenstiy Platoons	--	77	142	207

B2. VERIFICATION OF SIMULATION MODELS

The base scenarios are first validated and tested if specific parameters in the microscopic model are defined in the correct way. 15 simulations runs are carried out and Figure B 1 represents reoccurrence of a specific velocity distribution within VISSIM of the vehicle type trucks. The vehicle intensity of the trucks is set on 450 per simulation run. The mean velocity of trucks on the A15 corridor is set on 75.13 kilometers per hour.

The velocity distribution of cars is given in Figure B 2. This figure gives only an overview of the velocity that appeared frequently in the dataset of the output. Per simulation run the vehicle input for cars was set on 2750 vehicle per hour.

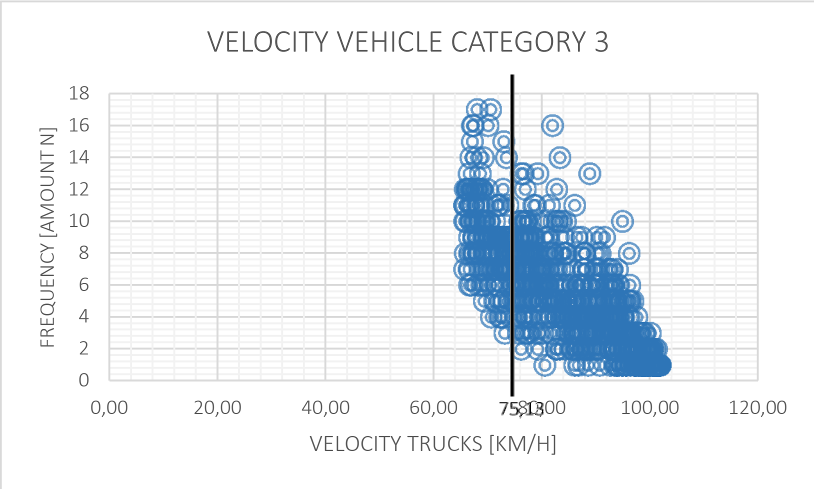


Figure B 1: The frequency of the speed distribution in VISSIM

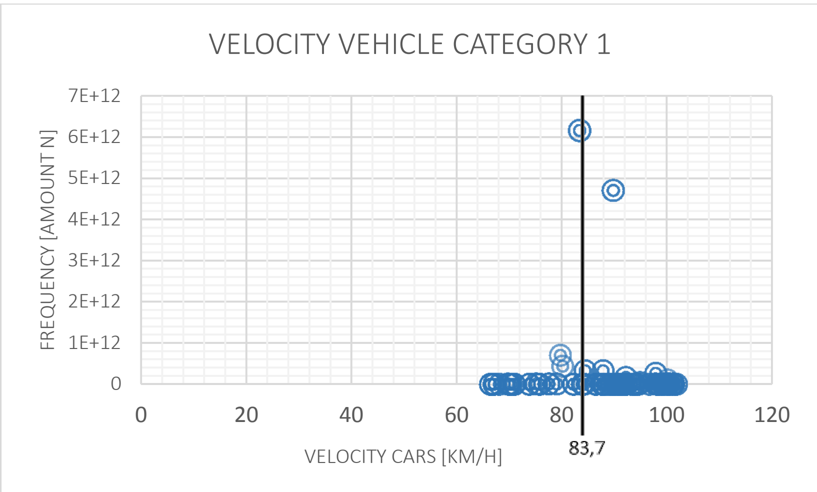


Figure B 2: The frequency of the speed distribution in VISSIM

B3. TRAFFIC NETWORK IN VISSIM WITH MEASUREMENT COLLECTION POINTS

To retrieve specific data from the two case areas, data collection points are placed on the network.

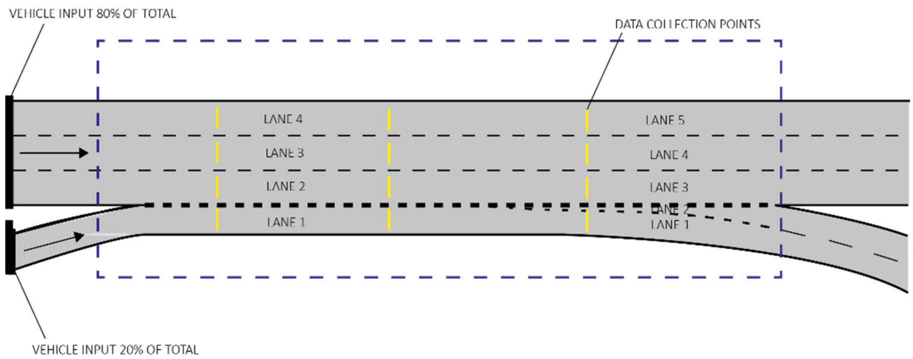


Figure B 3: Network lay-out with data collection points of the A15 corridor, case area 1, weaving area

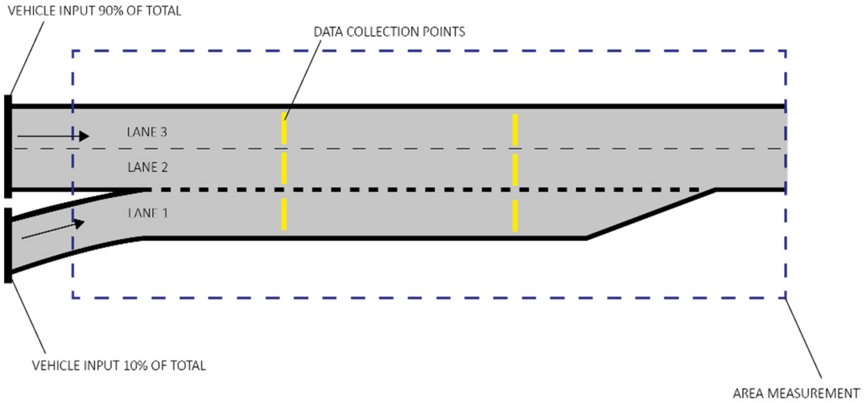


Figure B 4: Network lay-out with data collection points A15 corridor case area 2, merging area

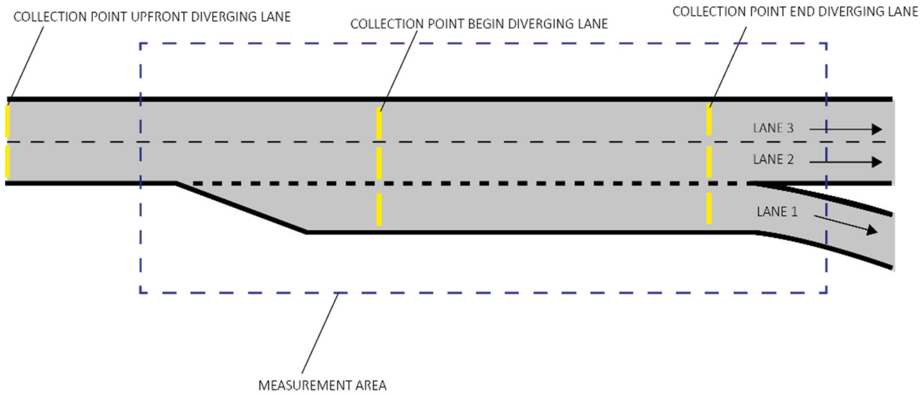


Figure B 5: Network lay-out with data collection points A15 corridor case area 2, diverging area

Case area 1 and 2 differ from each other because case area 2 has more destination traffic compared to case area 1. Therefor, the input of the vehicles is set differently within these two case areas. Case area 1, 20% of the vehicles merge and diverge on the A15 corridor. Case area 2, 10% of all vehicles diverge or merge on the network. Within the simulation model four different routing decisions are defined: (1) Travel along the A15 corridor, (2) Merging and travel along the A15 corridor, (3) Travel along the A15 corridor and exit the A15 corridor and (4) Merge on to the A15 corridor and diverge of the A15 corridor.

B4: OUTPUT OF THE EXPERIMENTS FOR CASE AREA 1 AND 2

The impact of platooning is analyzed for both case areas on traffic flow, jamming and safety. In this appendix the results are shown which support the overall analysis of the traffic locations.

B4.1 CASE AREA 1: WEAVING

The Travel time within the weaving area can be consider the samen when platooning is applied on the A15 corridor (Figure B 6). The travel time can be used to analyze the traffic flow. Platooning has an impact on queueing within the weaving area. Data collection points are set at the beginning, center and at the end of the weaving area. At the beginning of the weaving area platooning has the same impact as single trucks and jamming occurs at the A15 corridor (Figure B 7).

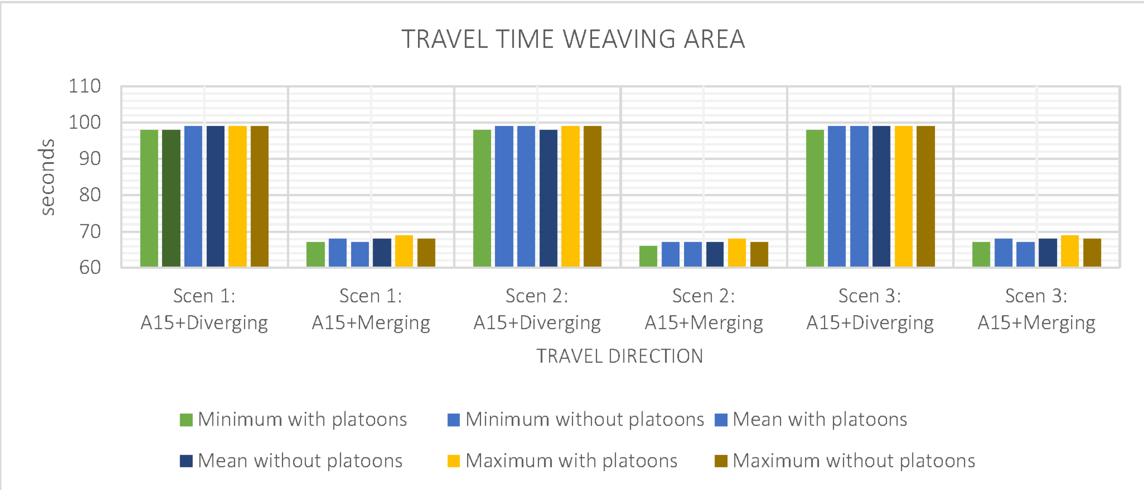


Figure B 6: Travel time within the weaving area of each scenario

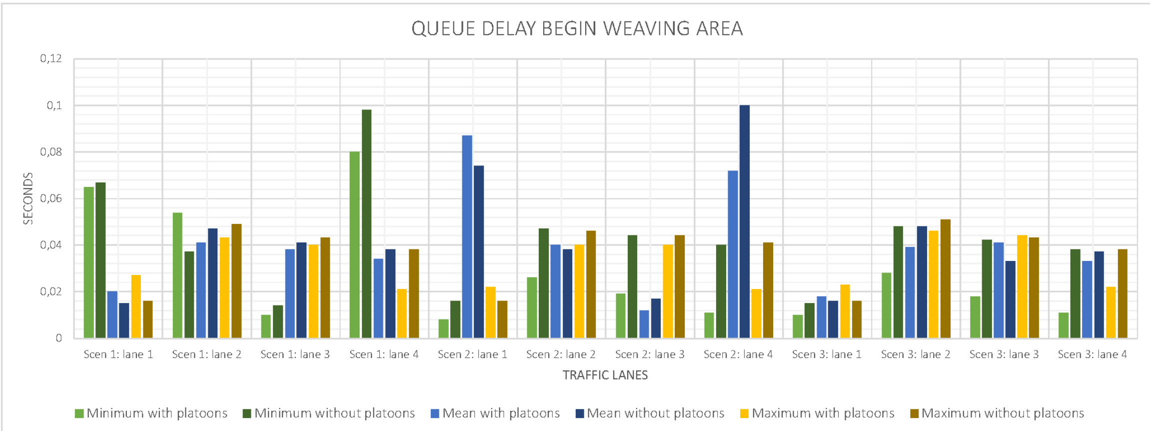


Figure B 7: Queue delay at the beginning of the weaving area

B4.2 CASE AREA 2: MERGING

The acceleration and deceleration behavior near the merging area is influenced by platooning on the road. This is visible in Figure B 8. The influence of truck platooning on the road is already at the beginning of the merging lane where vehicles start to decelerate to find a suitable gap on the adjacent lane (Figure B 9).

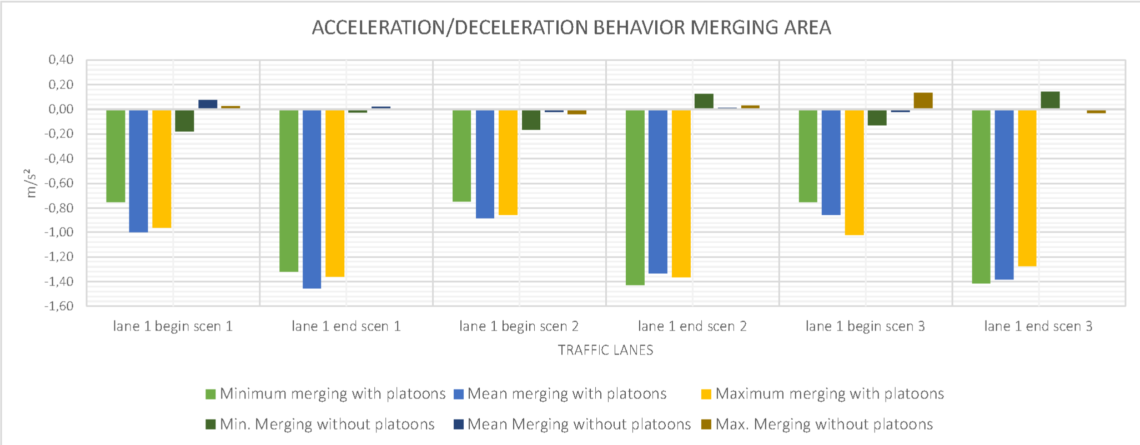


Figure B 8: Acceleration and deceleration behavior within the merging area to analyze the traffic flow

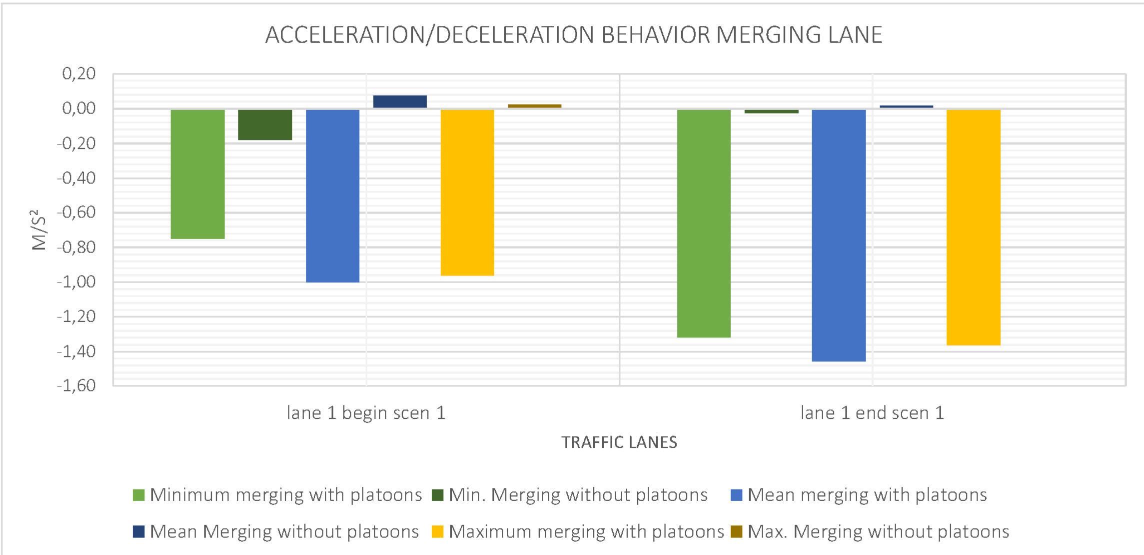


Figure B 9: Deceleration behavior on the merging lane during scenario 1, morning peak hour

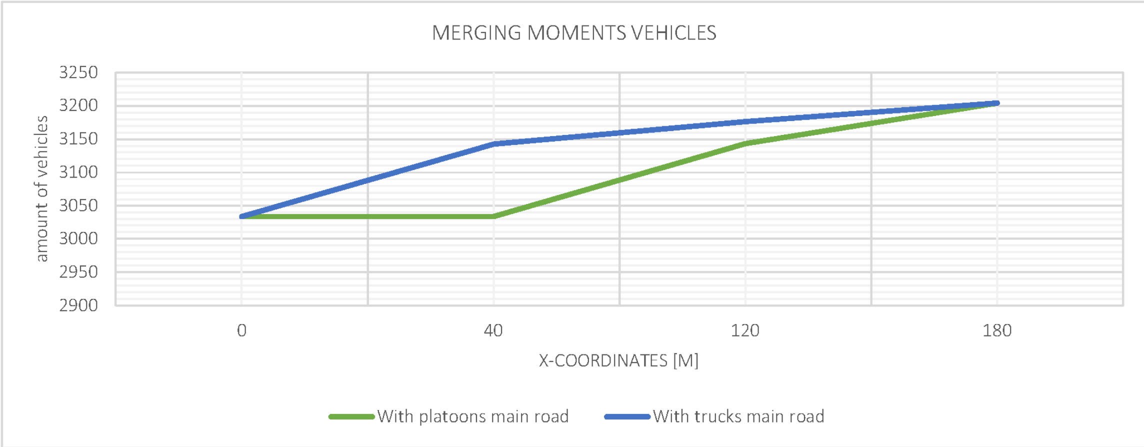


Figure B 10: Tipping point of vehicles when they merge on the main road. This is during scenario 3, with a mean intensity of platoons on the road.

Additionally, the stopped delay within the merging area increases extensively when a mean and maximum intensity of platooning is applied (Table B 2).

Table B 2: The increase and decrease of the stopped delay near the merging area of all three scenarios. The percentages correspond to Figure 34

	Scenario 1	Scenario 2	Scenario 3
Increase/decrease stopped delay mean intensity truck platoons	-66%	**100%**	72%
Increase/decrease stopped delay maximum intensity truck platoons	36%	71%	**100%**

B4.3 CASE AREA 2: DIVERGING

The acceleration and deceleration behavior within the diverging area is fluctuating continuously compared with the situation where single trucks drive on the road. This is not beneficial for the vehicles within the diverging area and can create traffic conflicts.

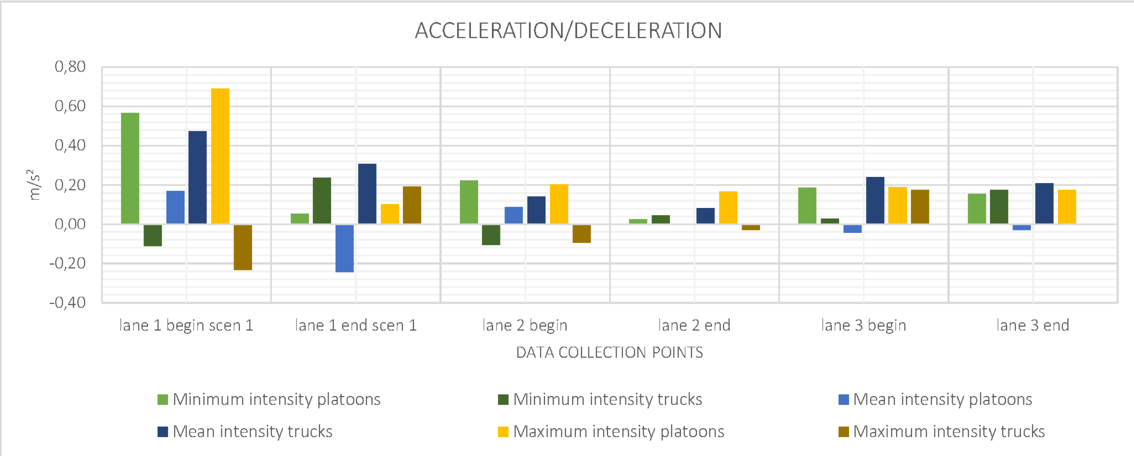


Figure B 11: Acceleration and deceleration behavior of vehicles within the diverging area of scenario 1, morning peak hour

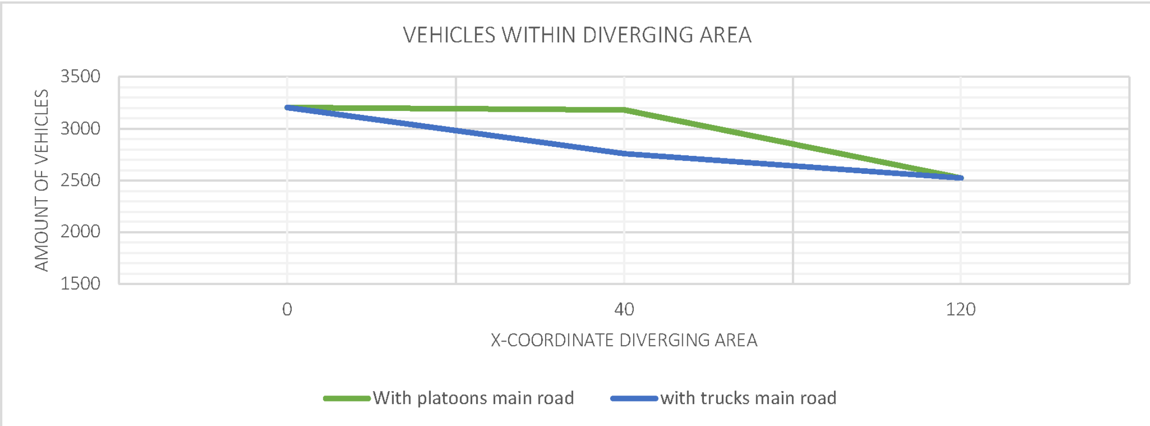


Figure B 12: Tipping point when vehicles want to diverge of the main road. This is during scenario 3 with a mean intensity of truck/platoons on the road.

C1: EXPERIMENTS OF THE TRAFFIC MANAGEMENT ROAD STRATEGIES

Each of the proposed road strategy is tested on the criteria traffic flow, efficiency and safety. In this appendix the results are shown which are used to create an overview of the impact of the road strategies on the traffic management stated in chapter 6. The road strategies are only tested for scenario 3 because the results are considered as an approximation. Road strategy are influenced by numerous of factors and some of these factors are not taken into account in this research.

C1.1 ROAD STRATEGY: SPEED DISTRIBUTION

The road strategy speed distribution is tested on the weaving, merging and diverging area. First, the results of the weaving area are discused. Secondly, the merging area and as last the diverging area. The road strategies are compared to the situation where truck platoons are on the road. With this analysis the road strategy can be analyzed if it is more efficient and safe compared to the situation where truck platoon obey the current traffic management of the A15 corridor.

The road strategy in figures is defined as: χ intensity road strategy. This means that an χ intensity of platoons is applied subjected to the traffic management of the road strategy.

χ Intensity platoons is the scenario where platoons are subjected to the current traffic management of the A15 Corridor.

WEAVING

The weaving area is assessed on traffic flow, efficiency and safety. The travel time is not affected within the weaving area with a fixed speed distribution (Figure C 1). The traffic efficiency is partially increased. With a maximum intensity of platoons the queue delay is less but with a minimum intensity of platoons on the road the queue delay within the weaving area increases. This also results in a decrease of traffic safety with a minimum intensity of platoons (Figure C 2 & Figure C 3).

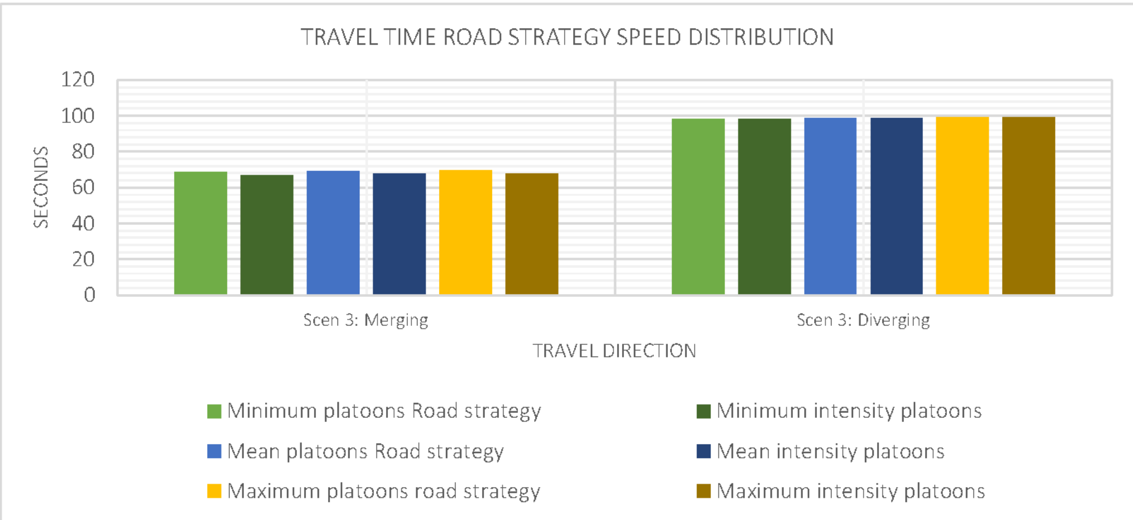


Figure C 1: Travel time of platoons subjected to the road strategy speed distribution within the weaving area during scenario 3

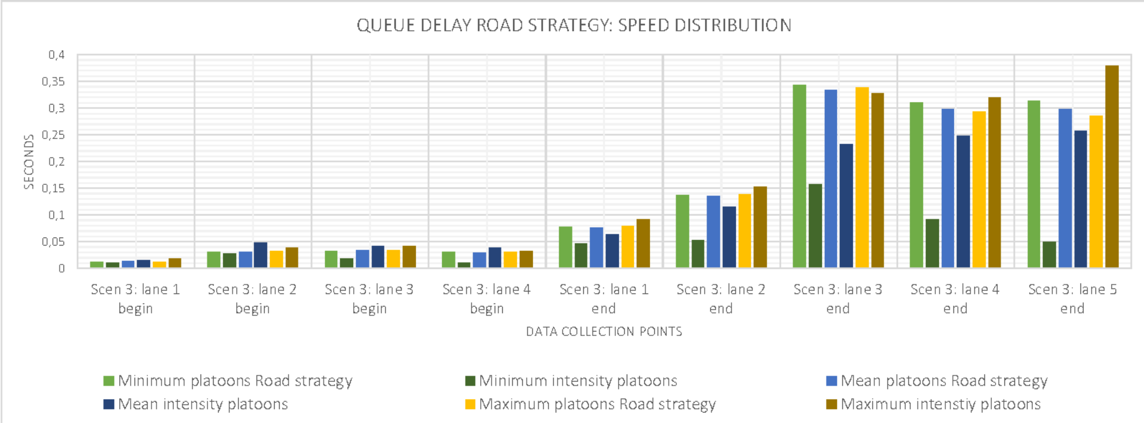


Figure C 2: Queue delay of platoons subjected to the road strategy speed distribution within the weaving area during scenario 3

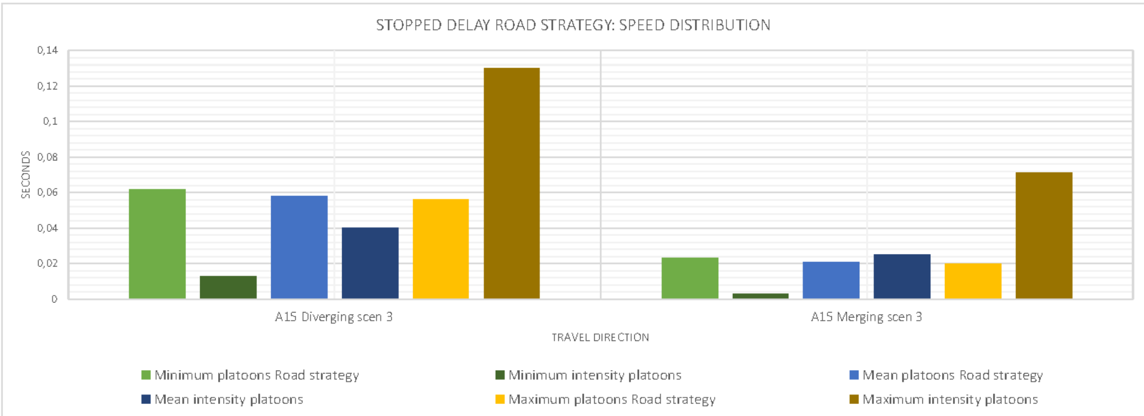


Figure C 3: Stopped delay of platoons subjected to the road strategy speed distribution within the weaving area during scenario 3

MERGING AREA

The travel time in the merging area is affected by the implementation of the road strategy. With a maximum intensity of platoons on the road the travel time is lower compared to platoons subjected to the current traffic management (Figure C 4). However, the traffic safety within the merging area is increased when a minimum and maximum intensity of platoons drive on the road (Figure C 6)

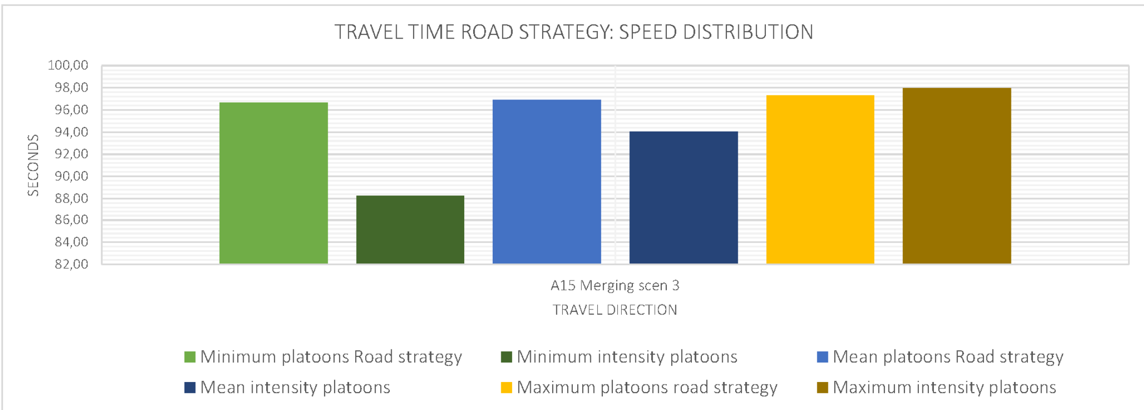


Figure C 4: Travel time of platoons subjected to the road strategy speed distribution within the merging area during scenario 3

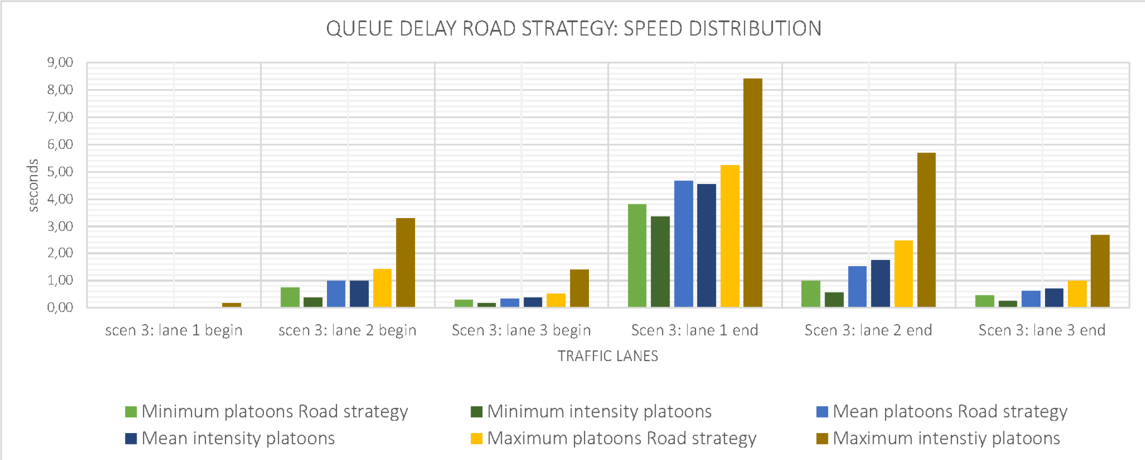


Figure C 5: Queue delay of platoons subjected to the road strategy speed distribution within the merging area during scenario 3

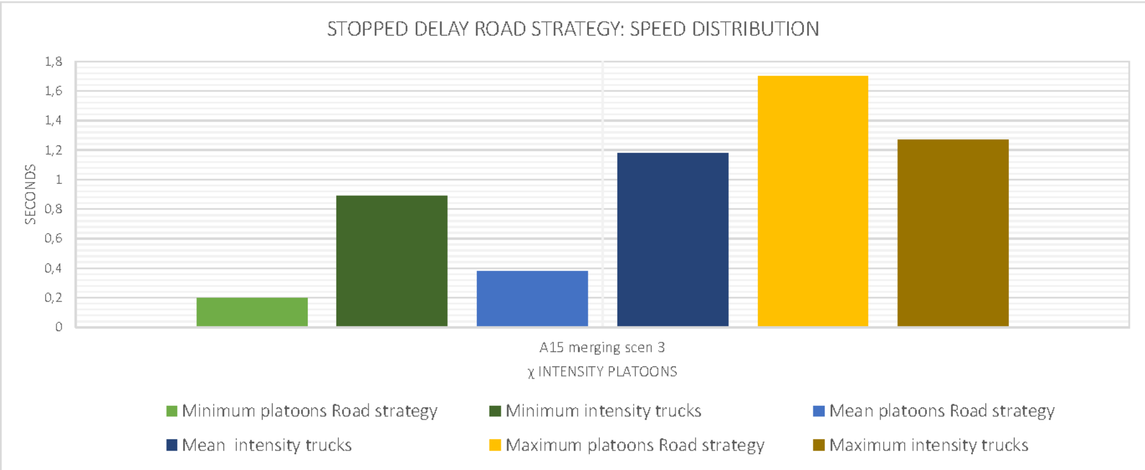


Figure C 6: Stopped delay of the platoons subjected to the road strategy speed distribution within the merging area during scenario 3

DIVERGING AREA

The road strategy within the diverging area has a negative impact on the travel time. The efficiency and safety is slightly increased. The safety with a minimum and mean intensity platoons is increased. The safety with a maximum intensity of platoons is decreased.

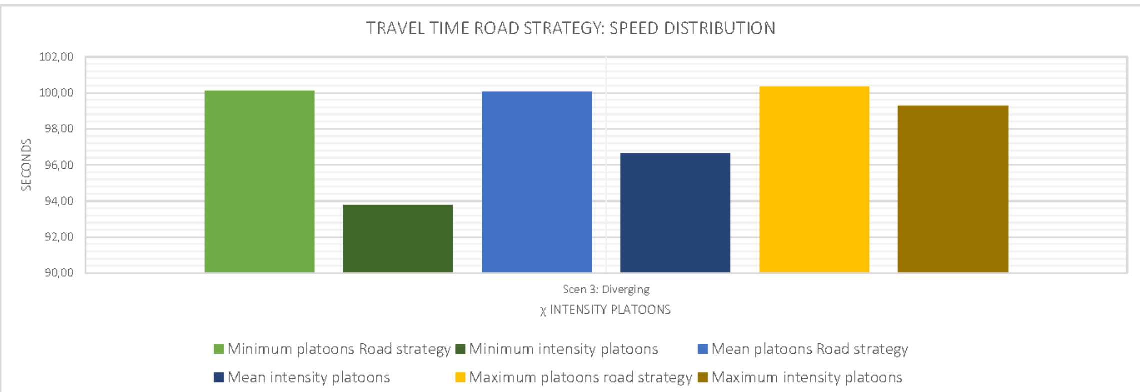


Figure C 7: Travel time of platoons subjected to the road strategy speed distribution within the diverging area during scenario 3

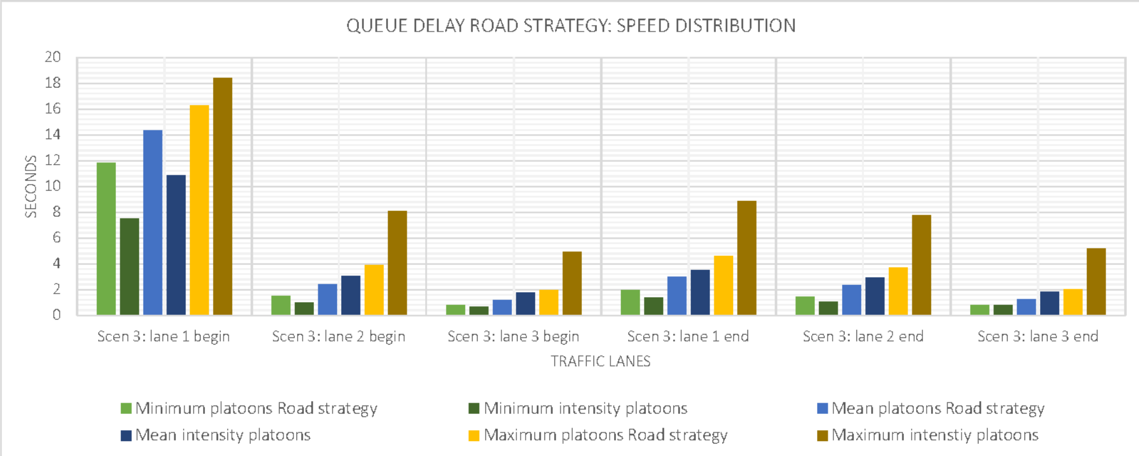


Figure C 8: Queue delay of the platoons subjected to the road strategy speed distribution within the diverging area during scenario 3

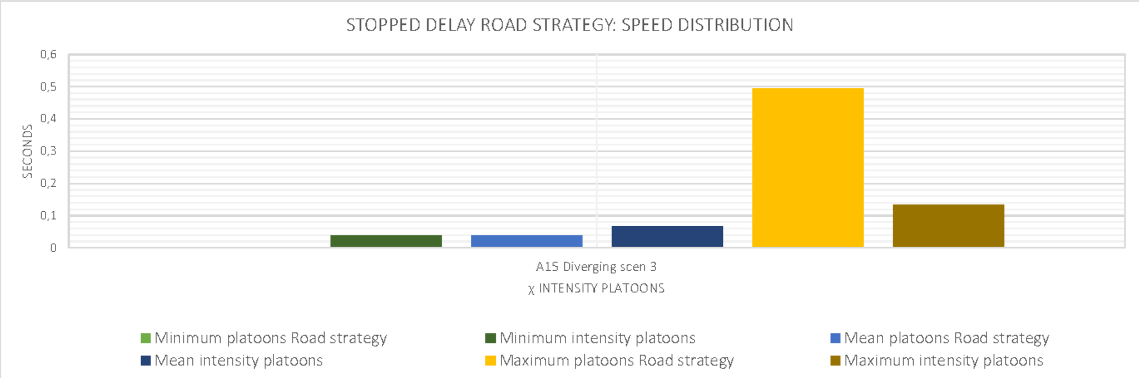


Figure C 9: Stopped delay of platoons subjected to the road strategy speed distribution within the diverging area during scenario 3

C1.2 ROAD STRATEGY: DYNAMIC MERGING AND DIVERGING LANES

The road strategy dynamic merging and diverging lanes is tested on the weaving, merging and diverging area. First, the results of the merging area and as last the diverging area. The road strategies are compared to the situation where truck platoons are on the road. With this analysis the road strategy can be analyzed if it is more efficient and safe compared to the situation where truck platoon obey the current traffic management of the A15 corridor.

The road strategy in figures is defined as: χ intensity road strategy. This means that an χ intensity of platoons is applied subjected to the traffic management of the road strategy.

χ Intensity platoons is the scenario where platoons are subjected to the current traffic management of the A15 corridor.

MERGING AREA

With longer merging lanes, vehicles might find a suitable gap on the adjacent lane and this could decrease the queue delay at the end of the merging area. This would increase the traffic safety. The travel time is increasing when a minimum and maximum intensity of platoons drive on the road. The merging lane is 50% longer compared to the current merging lane. Figure C 11 gives an overview of the queue delay. The data collection point 'center' is the end data collection point of the merging area without the extension. A longer merging lane increases the overall queue delay expecially for a minimum and maximum intensity of platoons. Thus, longer merging areas does not decrease the queue delay. A reason for this can be that vehicles expect that the merging lane becomes a normal traffic lane because they cannot oversee the whole road geometry of the merging lane. Due to these factors the safety is also not increased (Figure C 12).

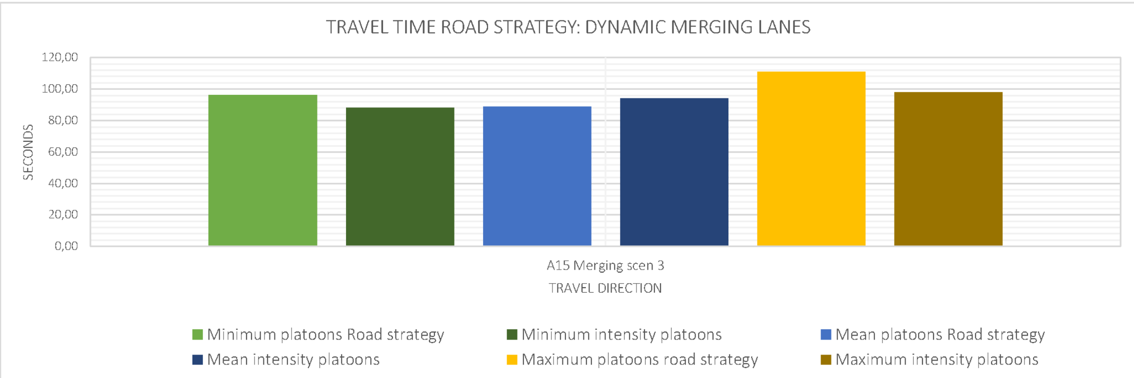


Figure C 10: Travel time of platoons subjected to the road strategy dynamic merging lanes within the merging area during scenario 3

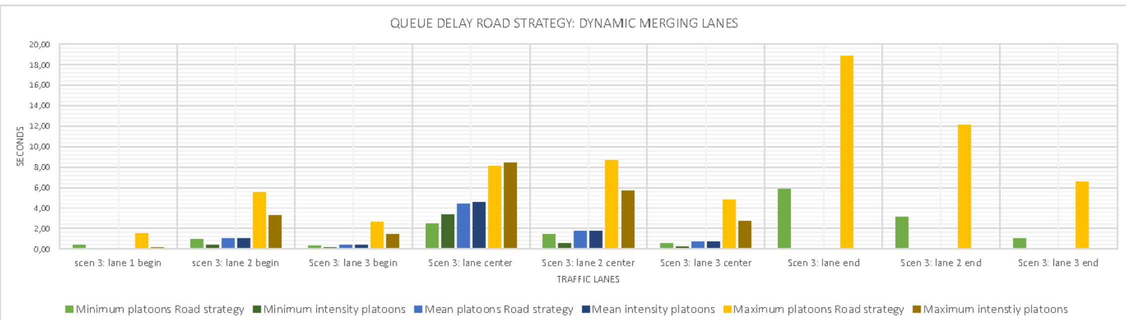


Figure C 11: Queue delay of platoons subjected to the road strategy dynamic merging lanes within the merging area during scenario 3

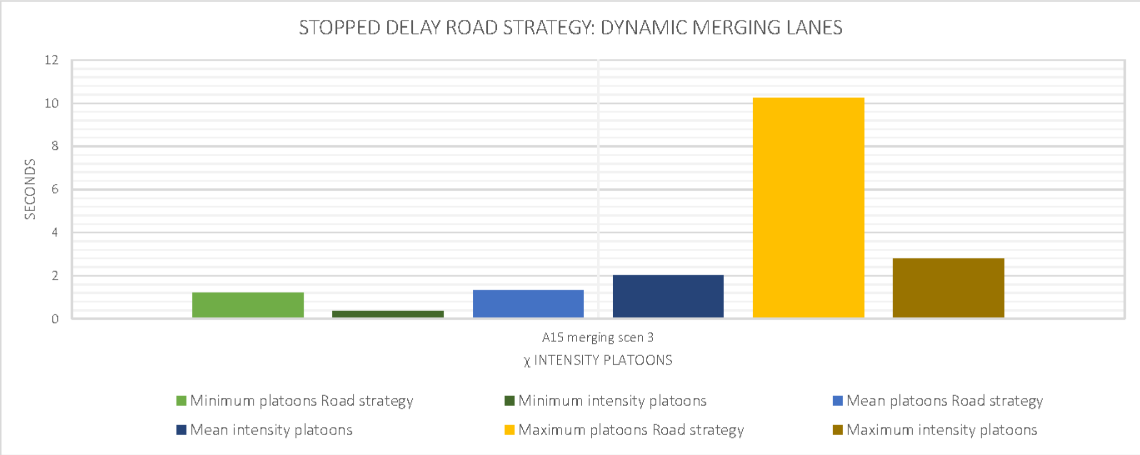


Figure C 12: Stopped delay of platoons subjected to the road strategy dynamic merging lanes within the merging area during scenario 3

DIVERGING AREA

With dynamic diverging lanes, performing lane changes to the deceleration lane might be more easier compared to the shorter diverging lane. The travel time is increasing when a minimum and maximum intensity of platoons drive on the road. The merging lane is 50% longer compared to the current merging lane. Figure C 13 gives an overview of the queue delay. The data collection point 'center' is the end data collection point of the merging area without the extension. A longer merging lane increases the overall queue delay expecially for a minimum and maximum intensity of platoons. Thus, longer merging areas does not decrease the queue delay. A reason for this can be that vehicles expect that the merging lane becomes a normal traffic lane because they cannot oversee the whole road geometry of the merging lane. Due to these factors the safety is also not increased (Figure C 15).

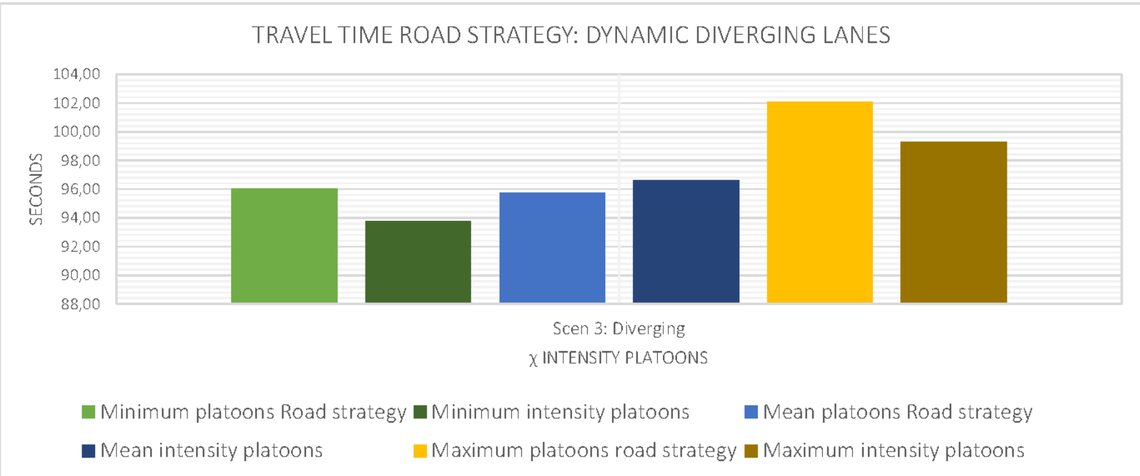


Figure C 13: Travel time of platoons subjected to the road strategy dynamic diverging lanes within the diverging area during scenario 3

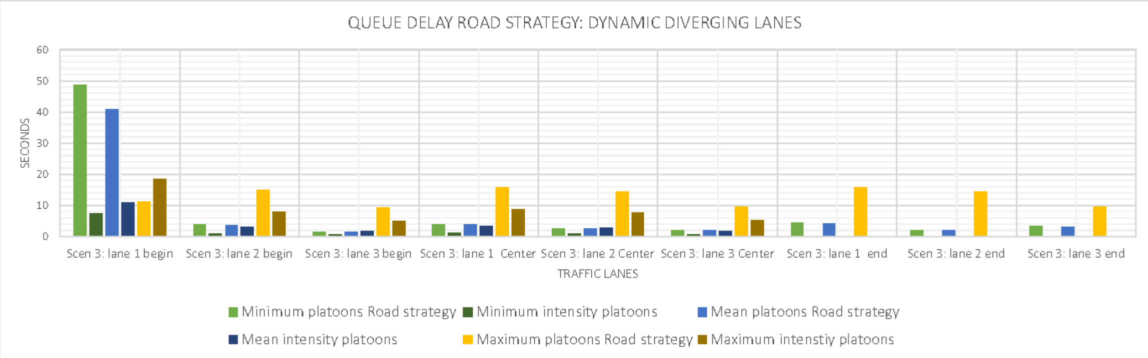


Figure C 14: Queue delay of platoons subjected to the road strategy dynamic diverging lanes within the diverging area during scenario 3

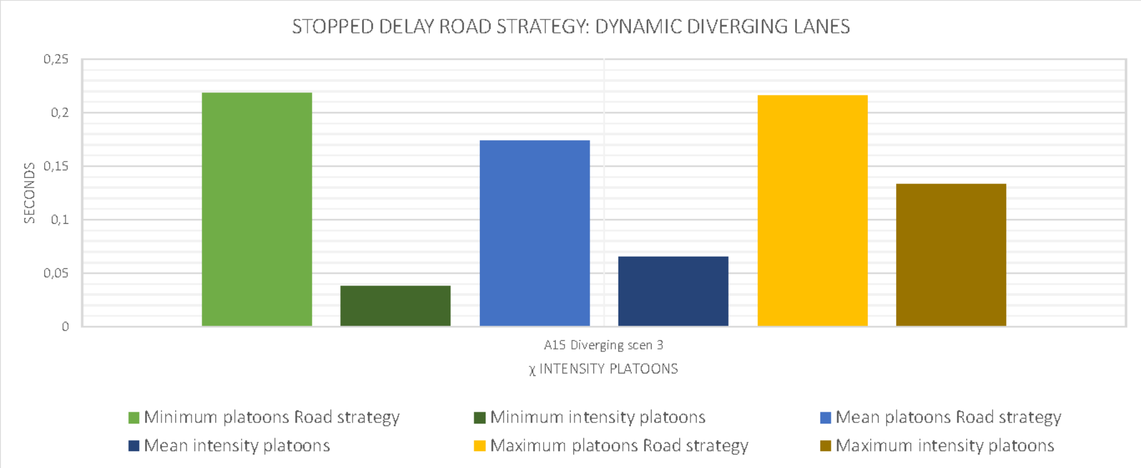


Figure C 15: Stopped delay of platoons subjected to the road strategy dynamic diverging lanes within the diverging area during scenario 3

C1.3 ROAD STRATEGY: LEFT LANE DRIVING PLATOONS

The road strategy left lane driving platoons is tested on the weaving, merging and diverging area. First, the results of the weaving area are discussed. Secondly, the results of the merging area and as last the diverging area. The road strategies are compared to the situation where truck platoons drive on the road. With this analysis the road strategy can be analyzed if it is more efficient and safe compared to the situation where truck platoon obey the current traffic management of the A15 corridor.

The road strategy in figures is defined as: χ intensity road strategy. This means that an χ intensity of platoons is applied subjected to the traffic management of the road strategy.

χ Intensity platoons is the scenario where platoons are subjected to the current traffic management of the A15 corridor.

WEAVING AREA

Trucks drive a longer distance compared to cars. To optimize the efficiecncy on the A15 corridor platoons could drive on the outermost left lane. With this road strategy platoons cannot form a blockage to other road users. Within the weavig areas the road strategy enhances truck platooning. The safety is increased and the travel time is equal to the scenario where platoons drive on the right side (Figure C 16 & Figure C 18).

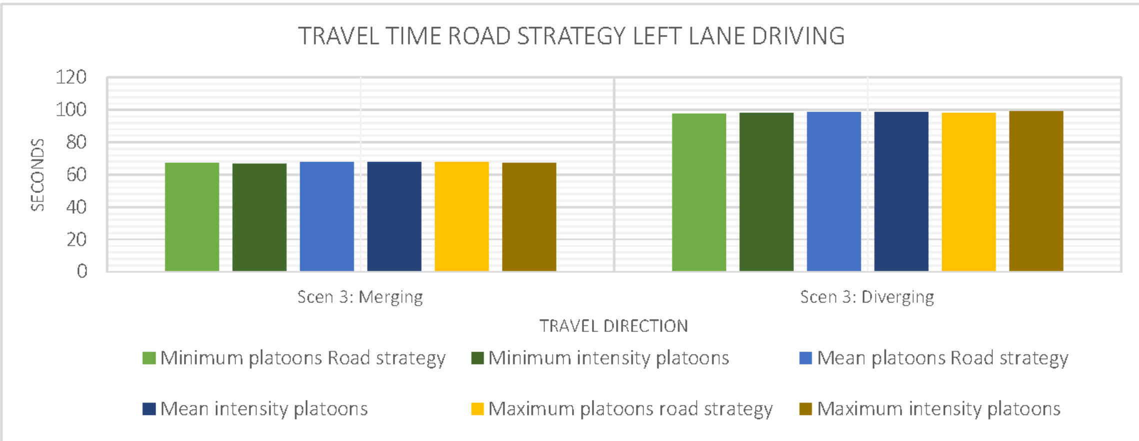


Figure C 16: Travel time of platoons subjected to the road strategy left lane driving in the weaving area during scenario 3

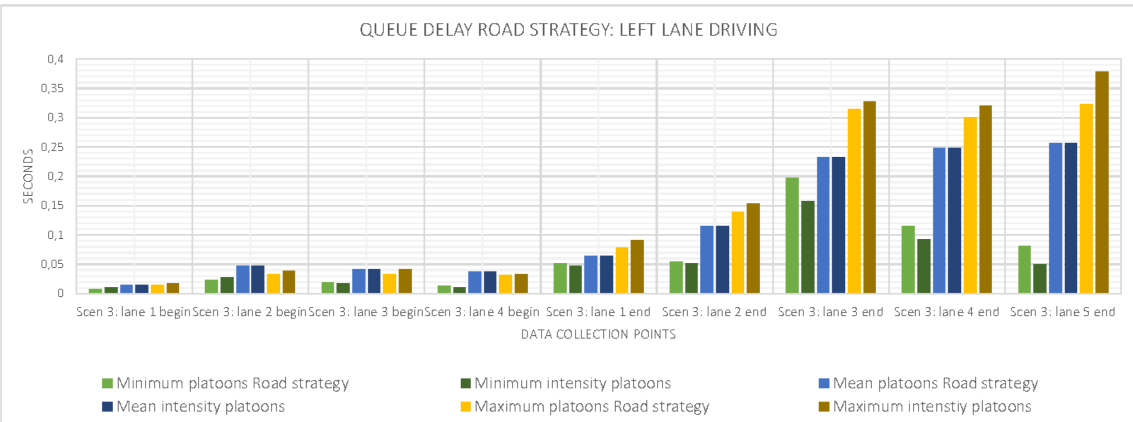


Figure C 17: Queue delay of platoons subjected to the road strategy left lane driving in the weaving area during scenario 3

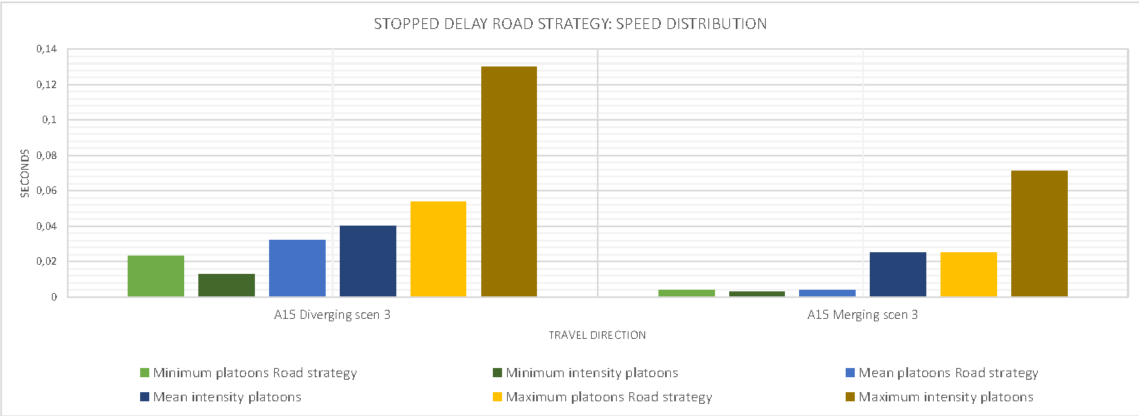


Figure C 18: Stopped delay of platoons subjected to the road strategy left lane driving within the weaving area during scenario 3

MERGING AREA

The merging area is characterized by the fact that it is a 2x2 traffic configuration. Left lane driving can be more of influence on this traffic configuration compared to a traffic configuration of 2x3. Less lanes are available to perform a lane change and vehicles drive on lane two with a higher speed that influences the merging behavior. The travel time increases for a minimum and maximum intensity of platoons (Figure C 19). This can be related to the fact that with these intensities of platoons the stop delay increases (Figure C 21). The queue delay for most lanes is decreased. However, on lane 3 it is increased (Figure C 20). This can be explained by the fact that more platoons drive on the road and platoons have a lower speed compared to cars.

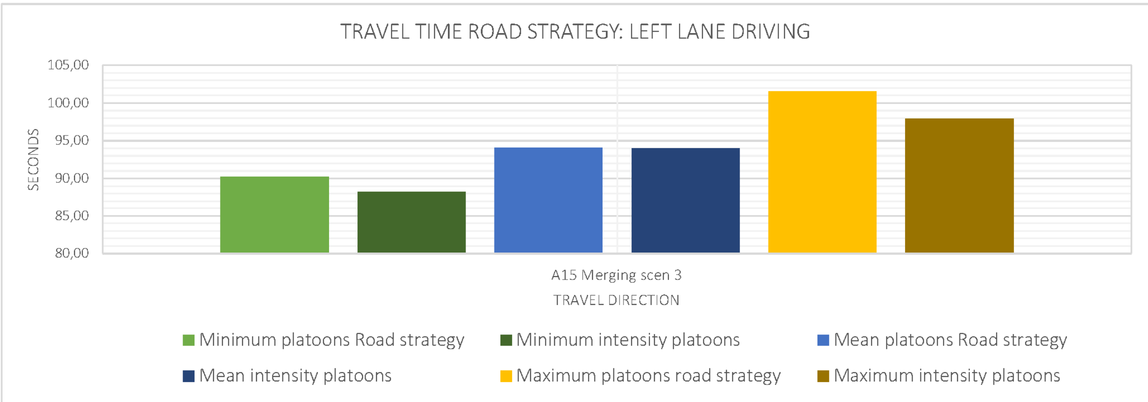


Figure C 19: Travel time of platoons subjected to the road strategy left lane driving within the merging area of scenario 3

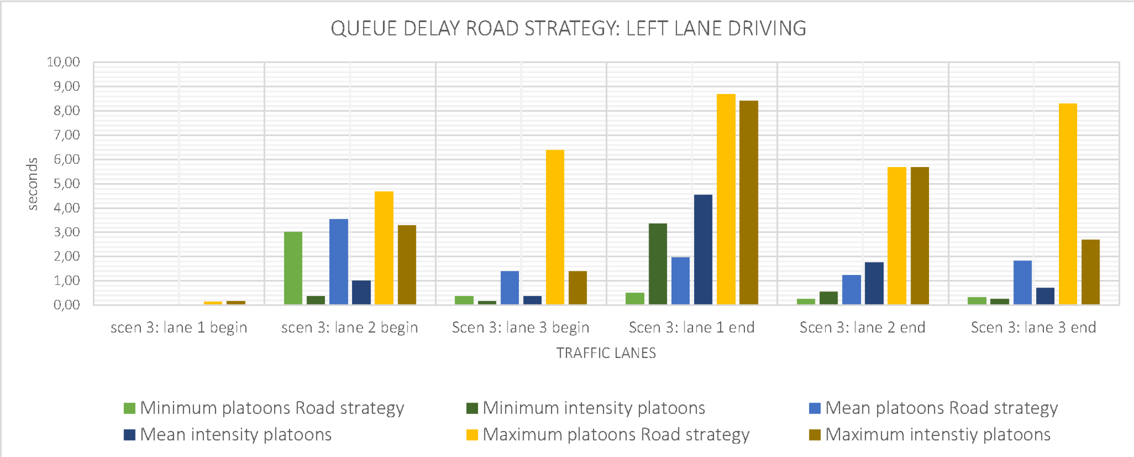


Figure C 20: Queue delay of platoons subjected to the road strategy left lane driving within the merging area during scenario 3

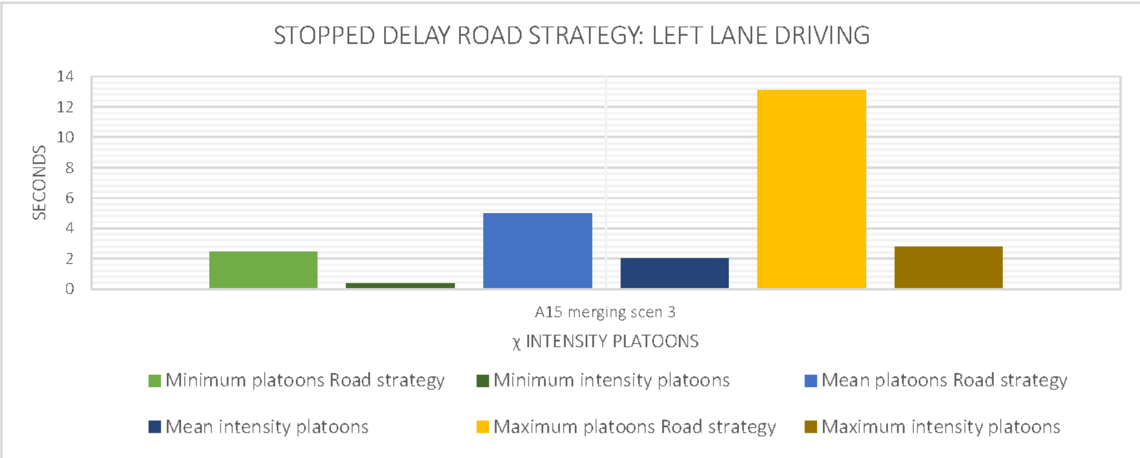


Figure C 21: Stopped delay of platoons subjected to the road strategy left lane driving within the merging area during scenario 3

DIVERGING AREA

The diverging area has a 2x2 traffic configuration. This road strategy has a negative impact on the travel time, queue delay and safety. A reason for this can be that platoons need to diverge as well and need a larger gap on the adjacent lane to merge. This can increase the queue delay and moving bottlenecks within and before the diverging area can occur.

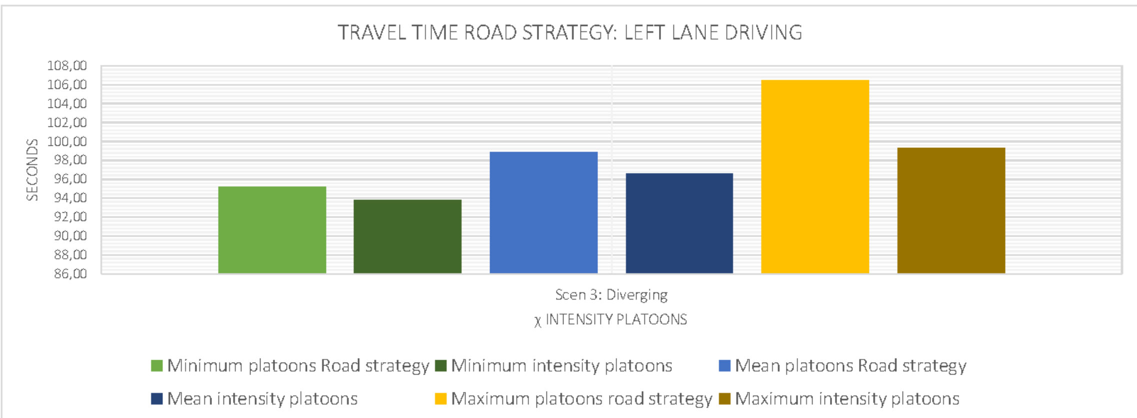


Figure C 22: Travel time of platoons subjected to road strategy left lane driving within the diverging area during scenario 3

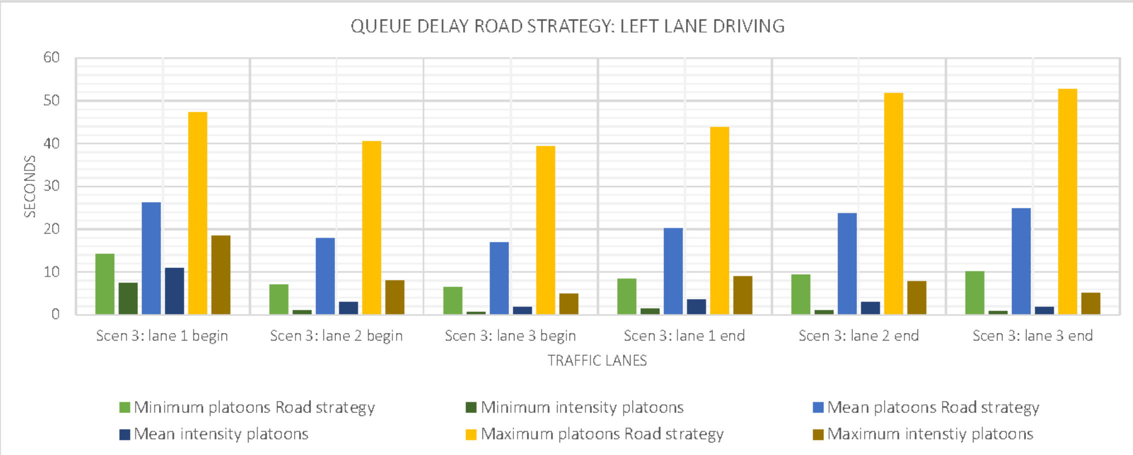


Figure C 23: Queue delay of platoons subjected to the road strategy left lane driving within the diverging area during scenario 3

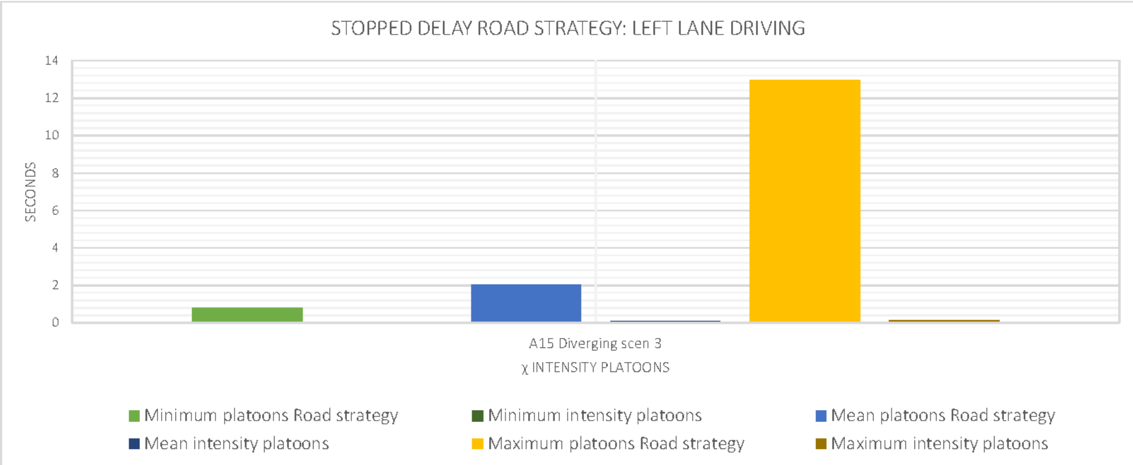


Figure C 24: Stopped delay of platoons subjected to the road strategy left lane driving within the diverging area during scenario 3