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Impacts of Truck Platooning at Motorway On-ramps

Analysis of traffic performance and safety effects of different platooning strategies and platoon configurations using microscopic simulation

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Preface

This thesis is the final fulfilment for obtaining the Master of Science degree in Civil Engineering – track Transport and Planning at the Delft University of Technology. The research has been conducted in association with ITS Edulab, a collaboration between the Dutch road authority Rijkswaterstaat and Delft University of Technology.

I would like to thank all the people that contributed to this research. First of all, I would like to thank my daily supervisor at TU Delft, dr. Meng Wang. His patience with my questions and my sometimes chaotic explanations during our bi-weekly meetings as well as his huge knowledge on the subject really helped me to make the right choices and successfully complete the research. Moreover, I would like to express my gratitude to my supervisor at Rijkswaterstaat, drs. Onno Tool. With his practical experience and willingness to invest time in me, he gave me extensive feedback from the point of view of the road authority and introduced me to many colleagues that gave me important information to improve the quality of the research. He and his colleagues at Rijkswaterstaat have always made me feel welcome. Furthermore, I would like to thank the chairman of my committee, prof. dr. ir. Bart van Arem, for his help in establishing the topic, his faith in me that I would be able to research such a topic well and his constructive feedback during the official meetings. Special thanks also go to dr. ir. Riender Happee, for his detailed feedback and tips on the preliminary reports which he always read thoroughly and on the presentations during the official meetings. I am also very grateful for the indispensable help with programming I received from ir. Wouter Schakel. Without your patience in answering all my questions and e-mails I could never have conducted this research. I would like to thank Henk Taale for giving me the opportunity to join ITS Edulab to conduct my master thesis and my fellow students at the 'afstudeerhok' at the faculty for the nice talks, good laughs and of course their support. Finally, I want to thank my family and especially my wife for her unconditional support even though I came home late so often.

Hopefully this research can help to facilitate and regulate the introduction of automated truck platoons on the motorway in the Netherlands and can shed some light on the challenges related to this introduction for Rijkswaterstaat as road authority.

Sander van Maarseveen

Delft, December 2017

Summary

This research addresses automated driving (AD) of trucks in platoons: truck platooning. Truck platooning is defined as two or more trucks driving at reduced inter-vehicle gaps (typically less than one second, corresponding with a distance of less than 22 m at 80 km/h) enabled by wireless vehicle-to-vehicle communication and of which both longitudinal and lateral control are automated.

As automated vehicles on public roads become more common, road authorities have to consider action to facilitate and regulate their introduction. Before truck platooning can be introduced, platooning technology will have to prove itself safe and reliable. A main challenge lies in the largely unknown effects of the introduction of automated vehicles on mixed (conventional and automated) traffic and the nonconformity in the effects that have been researched (Calvert et al. 2016). Because the complexity of traffic dynamics on motorways is relatively low, motorways will most likely be the first type of road where automated driving will be introduced. Moreover, given the financial advantages for carriers, truck platooning on motorways might well become one of the first large-scale applications of automated driving.

The motorway merging behaviour of human drivers in the presence of truck platoons is still largely unknown. Similarly, the desired behaviour of a truck platoon in such a situation is also still largely unknown. When truck platooning on the motorway is introduced, safety issues such as crashes or merging problems can occur when human drivers want to merge on the motorway at an on-ramp if the right lane is (partially) blocked by a truck platoon. Moreover, traffic performance issues such as a breakdown of traffic can occur due to unexpected braking manoeuvres, resulting in additional traffic jams. A (temporary) decrease in traffic performance may occur if truck platoons are unable to perform at the same overall level as human drivers, which might not be accepted by road authorities if this drop in performance lasts too long.

Research to identify and quantify the traffic performance and safety effects of truck platooning on the motorway at on-ramps before deployment in practice is thus necessary. In this research, this is done by modelling driving behaviour of both truck platoons and conventional vehicles in mixed traffic on the motorway using microscopic simulation, for the specific case of truck platoons passing a motorway on-ramp. Thereby insights are acquired into the impacts of truck platooning at motorway on-ramps in mixed traffic on traffic performance and safety. The main research question therefore is:

What are the traffic performance and safety effects of truck platooning on the motorway in the situation of conventional vehicles merging at an on-ramp for different platooning strategies and platoon configurations?

Automated driving controller framework for truck platoons

To answer this question, a literature review was first conducted on the modelling of automated driving of truck platoons. For the car-following behaviour, different gap regulation strategies were explored as well as different communication lay-outs with other vehicles. Based on the findings, a multi-anticipative Cooperative Adaptive Cruise Control (CACC) controller using a constant time gap strategy (**equation (1)**) was chosen as longitudinal controller for the trucks equipped with AD technology, since it was found to generate the most plausible driving behaviour with respect to string stability and safety and is in line with the most practical, acceptable and common application of CACC as well as with what is most likely applied by OEMs (Ioannou and Chien 1993, Naus et al. 2010). If the equipped trucks cannot communicate with their predecessor because it is unequipped, the CACC controller is reduced to ACC and in case the leading vehicle is out of the sensor range, cruise control functionality is used. A collision avoidance system was added to the controller as a safety mechanism that can perform sufficiently hard braking to avoid a collision in critical conditions, such as approaching a jam tail.

The performance of the controller was verified in simulations of multiple typical driving scenarios representing common traffic situations, among which a stop-and-go traffic scenario mimicking a traffic jam, an emergency braking scenario and a vehicle cut-in scenario. Based on the results, it was determined that equipped trucks will only communicate with their immediate predecessor and that the collision avoidance system can guarantee collision-free driving in critical conditions. The control parameters of the controller were thereby tuned to enable a smooth acceleration response similar to

that of a human driver, to show string-stable behaviour in which disturbances are attenuated in upstream direction and to guarantee collision-free driving.

$$a_{i,t}^{car-following} = k_s (s_{i,t} - s_{i,des,t}) + k_{\Delta v} R(s) (v_{i-1,t} - v_{i,t}) + k_a a_{i-1,t} \quad (1)$$

Where $a_{i,t}^{car-following}$ denotes the desired acceleration of the platooning truck, $(s_{i,t} - s_{i,des,t})$ the deviation of the inter-vehicle distance gap from the desired gap, $(v_{i-1,t} - v_{i,t})$ the relative speed difference with the predecessor, $R(s)$ the collision avoidance function, $a_{i-1,t}$ the communicated acceleration of the predecessor in the previous time step and k_s , $k_{\Delta v}$ and k_a control parameters.

Several important design choices were made for the automated driving in the simulations:

- **The equipped trucks always drive automatically.**
Depending on whether the predecessor is also an equipped truck, the proximity of that predecessor and whether the maximum platoon size has already been reached, the equipped truck will either use CACC, ACC or cruise control functionality.
- **Automated driving is only applied for longitudinal driving.**
Lane change decisions are still only made by the human truck drivers to ensure realistic lane change decisions.
- **Platoon formation takes place in the network ('on-the-fly').**
Platoons are only formed after vehicle generation. This is because the vehicle generator cannot distinguish whether the platooning conditions are satisfied before vehicles exist. The road network used is therefore long enough to make sure the truck platoons have been formed before reaching the on-ramp.
- **Equipped trucks only initiate platoon formation if their predecessor is close enough.**
An equipped predecessor is considered close enough if the inter-vehicle time gap is smaller than the sensor detection range (approximately 300 m) and if the estimated time it takes to complete a platoon formation manoeuvre is acceptable.
- **Equipped trucks initiate platoon formation by catching up with their equipped predecessor.**
Having the potential platoon follower speed up instead of the potential platoon leader to slow down prevents negative effects of truck platooning caused by lower average speeds of trucks. The catch-up speed is slightly higher than the normal desired speed and stochastic to match variability in vehicle driving behaviour as observed in reality.
- **The function that truck platoon members can create gaps ('yield') for other vehicles can either be turned on or off.**
When this function is turned off, platoon members will not yield for merging vehicles at the on-ramp if they notice an urgency to merge. The platoon will thus never be disengaged on the initiative of one of the platoon members.
- **The function that truck platoon members can perform discretionary or cooperative lane changes can either be turned on or off.**
When this function is turned off, none of the platoon members is allowed to perform discretionary or cooperative lane changes once a platoon has been formed. As long as the platoons remain intact none of the platoon members will therefore change lanes to be able to maintain their desired speed or to create a gap for merging vehicles.

Simulation of human driving behaviour

A literature review was also conducted on the simulation of human driving behaviour. Existing car-following and lane change models as well as existing microscopic simulation tools were explored to determine their suitability for modelling human driving behaviour, especially merging behaviour at motorway on-ramps in mixed traffic with truck platoons. It was found that many of the current models have difficulty with simulating traffic behaviour at motorway on-ramps (Daamen et al. 2010), (Broekman 2017). The main factors influencing motorway merging behaviour are the merge location and its relation to prevailing driving conditions, gap acceptance and the relaxation phenomenon. Courtesy yielding and cooperative lane changing seem to have a significant effect on merging behaviour as well (Daamen et al. 2010), but most models fail to model this behaviour well. However, the more recent **Lane-change Model with Relaxation and Synchronization (LMRS)** (Schakel et al. 2012) takes away some of these shortcomings by introducing a new decision structure and interaction with car-following in the form of relaxation and synchronization. Relaxation is the phenomenon of slowly decelerating upon completing a lane change in order to increase the gap to the desired gap. Synchronization is the phenomenon that a vehicle adapts its speed to the speed of the vehicles in the target lane when about to execute a lane change manoeuvre. At the same time, the LMRS incorporates only seven parameters, making it relatively easy to calibrate. The LMRS is implemented in the microscopic simulation tool **MOTUS** (TU Delft 2017). MOTUS also incorporates an adapted version of the car-following model **Intelligent Driver Model (IDM+)** (Schakel et al. 2012), which was also found to perform well compared to the other models explored.

Apart from the performance of the incorporated behavioural models, several other requirements were defined for choosing a simulation tool. The most important requirements were the possibilities of adapting the model to incorporate AD, the possibility to generate the desired output and the availability of technical support. Thereby it was determined that MOTUS was the best choice to simulate truck platooning at motorway on-ramps in mixed traffic. Therefore, MOTUS was chosen as simulation tool and adapted to incorporate AD for truck platoons.

Behavioural adaptation

The final part of the literature review researched behavioural adaptation of human drivers in the presence of truck platoons. By adapting the simulation model to incorporate these behavioural adaptations, the validity of the modelling was improved. Unfortunately, there is little empirical evidence on what these adaptations are since truck platooning is not commonly applied in practice yet. However, some information from a truck platooning field test is available and some platooning effects can be observed from observations from a busy motorway freight route. Research findings on the deployment of longer and heavier vehicles (LHVs) on the Dutch motorways in recent years also give some clues on possible behavioural adaptations. This empirical research reveals that human drivers tend to adapt their driving behaviour when driving in the proximity of or interacting with truck platoons on the motorway. The most important finding is that drivers tend to accept smaller gaps when merging if many trucks are driving closely behind each other in the right lane. This may have a detrimental effect on safety. Also, merging vehicles generally merge later and may even fail to merge in time so that they either have to stop at the end of the acceleration lane or continue driving on the shoulder lane, both of which is undesirable. Given the findings, *behavioural adaptation was therefore incorporated in MOTUS by decreasing the minimum gap accepted by human drivers when merging in front of an equipped truck*. The minimum accepted gap can be such that the resulting gap with the putative equipped follower after completing the merging manoeuvre is as low as 0.3 s, depending on the urgency of the merging manoeuvre.

Model validation

The adapted simulation model MOTUS, now incorporating AD for truck platoons as well as behavioural adaptation of human drivers in the presence of truck platoons, was applied using the standard model parameters that have been calibrated to represent Dutch motorway traffic (Schakel et al. 2012). The performance of the adapted model was further checked by comparing the performance on a two-lane motorway section with on-ramp to findings from empirical evidence on motorway traffic in general and on the findings on the behavioural adaptations more specifically. The performance of the adapted simulation model was thereby verified.

Experimental design

To quantify the impacts of truck platooning, simulation scenarios were defined. Different truck platooning strategies are considered:

- **Fixed inter-vehicle gaps**
In this strategy, the platoon members will always maintain their desired inter-vehicle gaps, regardless of whether other vehicles want to change lanes towards the platoon.
- **Allow yielding**
In this strategy, the platoon members can yield for a vehicle in the adjacent lane to create a gap when that vehicle needs to perform a forced lane change.
- **Allow lane changing**
In this strategy, the platoon members can perform courtesy lane changes to create a gap for a vehicle in the adjacent lane when that vehicle needs to perform a forced lane change.

Moreover, different truck platoon configurations are considered:

- **A maximum platoon size of two trucks or three trucks.**
A platoon in the simulations is never larger than the maximum platoon size.
- **A desired CACC inter-vehicle gap of 0.3, 0.5, 0.7 or 0.9 s.**
The smallest gap of 0.3 s corresponds to the current minimum of what is technically possible. The larger gaps of 0.5 and 0.7 s are also common for CACC, but result in longer platoons that form a longer barrier for merging traffic. The gap of 0.9 s is larger than the minimum gap accepted by merging vehicles, so that the effects if vehicles can also merge within a truck platoon can be observed.

The platooning strategies and platoon configurations are applied on a two-lane motorway section of 6 km with an on-ramp in the validated simulation model MOTUS that was adapted to incorporate CACC for truck platoons. Different traffic intensities are applied in the simulations: low, medium and high traffic intensities, representing empirical data from the A67 motorway between Eindhoven and Venlo in the Netherlands, a busy freight corridor between the ports of Rotterdam and Antwerp and the German hinterland, making it very suitable for truck platooning (Bakermans 2016). A congestion scenario was added to capture the effects of truck platooning in congested conditions. Moreover, different penetration rates of equipped trucks are applied: 0%, 25%, 50%, 75% and 100% to represent different stages of the introduction of truck platooning on the motorway. The simulation variables are combined for all possible combinations, resulting in a total of 388 simulation scenarios. The simulation scenarios are each run for twenty seeded runs, each run representing one hour of traffic. Thereby a time step of 0.2 s is applied.

Simulation results

Initially, the simulation results for the 'fixed inter-vehicle gaps' platooning strategy were assessed. The simulation results show that truck platooning can have a significant impact on the on-ramp merging behaviour of human drivers. The average merge locations shift slightly towards the end of the acceleration lane, but more importantly and in contrast to the reference case without truck platooning, a significant number of vehicles is unable to merge within the length of the acceleration lane. The severity of this problem increases with increasing on-ramp traffic intensity and the number of equipped trucks as shown in Figure 1. The figure shows the average shares of merging vehicles that are unable to merge in time for the different traffic intensities, aggregated for the different maximum platoon sizes and CACC time gaps. The lowest and highest observed values are also displayed. These bandwidths are caused by the differences between the maximum platoon sizes and CACC time gaps applied in the simulations. At equipped truck penetration rates below 25%, less than 1% of the merging vehicles is unable to merge. In free flow, the number of vehicles unable to merge can increase up to 60 per hour and in congestion even up to 90 per hour, corresponding to approximately 5% and 9% of the total number of merging vehicles. Even at a penetration rate of only 25%, already a few vehicles per hour are unable to merge.

Although vehicles that are not able to merge in time are simply deleted in the simulations, in reality they will still need to merge, which they could either do from standstill with a very high collision risk or by driving on the shoulder lane, both of which is undesirable and dangerous. This may lead to increased disruptions in the traffic flow in reality. Also, merging speeds drop by approximately 10

km/h in the last 50 m of acceleration lane on average in case of free flow compared to the reference case without platooning.

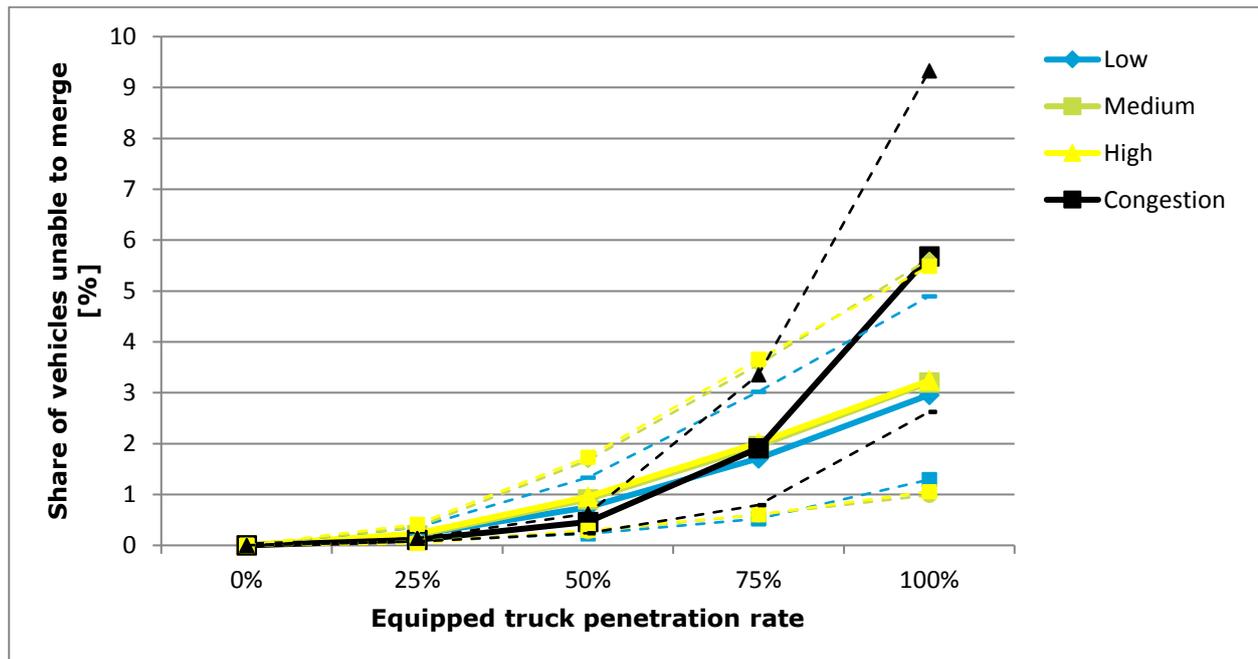


Figure 1: Share of vehicles unable to merge per traffic intensity. The averages are displayed as continuous lines and the highest and lowest observed values as dashed lines.

The safety effects of truck platooning were also measured using surrogate safety indicators. Both inter-vehicle gap distributions and time-to-collision (TTC) distributions were analysed. In that way it was revealed that no extra unsafety is caused by truck platooning, since the number of observations of dangerously small TTC values or inter-vehicle gaps does not increase.

Moreover, it was found that truck platooning in free flow hardly affects the maximum outflow downstream of the on-ramp. The congestion scenarios however reveal a potential road capacity increase of approximately 2% with 200 equipped trucks/h up to 19% with 800 equipped trucks/h on average. This is caused by higher average flows in the right lane due to the platooning trucks driving at reduced time gaps. Thereby the congestion also becomes a little less severe: the onset of congestion takes a few minutes longer and the average speeds in congestion are slightly higher. Furthermore, in congestion the average speed difference between the left and the right lane increases due to truck platooning. This is caused by higher speeds in the left lane, possibly caused by less interaction between the lanes because the truck platoons do not change lanes. These increased speed differences could lead to dangerous situations.

Differences in effects between the platoon configurations

Significant differences in the effects of truck platooning were revealed between the different platoon configurations. The differences between the platoon configurations are larger with increasing penetration rate of equipped trucks. It is observed that larger platoon sizes increase merging problems considerably. Up to twice as many vehicles may be unable to merge in scenarios with a maximum platoon size of three trucks compared to scenarios with a maximum platoon size of two trucks. At the same time the capacity in scenarios with a maximum platoon size of three trucks instead of two trucks can increase with up to 8% extra, but the increase is only significant for equipped truck penetration rates above 25%. It is also observed that as long as CACC time gaps applied by truck platoons are smaller than the minimum acceptable gap for merging vehicles, the number of vehicles unable to merge in time will considerably increase with increasing CACC time gap. Up to three times as many vehicles may be unable to merge in scenarios with a CACC gap of 0.7 s compared to scenarios with a CACC gap of 0.3 s.

Possible solutions to merging problems

If truck platoon members are allowed to yield for merging vehicles to create a gap (the 'allow yielding' strategy), **merging problems are solved. No merging vehicles are unable to merge in time any more.** Instead, those vehicles now merge within the last 100 m of acceleration lane. The

differences between the platoon configurations are reduced to almost zero. The yielding does not lead to extra unsafety on the motorway. Due to the fact that more vehicles are merging, the traffic flow in the right lane gets disrupted slightly more at the on-ramp. This results in a slight reduction of the positive effects of truck platooning on maximum outflow downstream of the on-ramp and capacity. A potential capacity increase of 15% (was 19% with the 'fixed gaps' strategy) with 800 equipped trucks/h still remains if all vehicles would merge in time.

The 'allow courtesy lane changing' strategy is also able to reduce merging problems, but only in congestion. Up to 50% fewer vehicles are unable to merge in time. In free flow the speed difference with the left lane is simply too large for the truck platoons to be able to change lanes safely. Similarly, truck platoons driving with a CACC time gap larger than the minimum gap accepted by merging vehicles can also reduce merging problems, but now only in free flow. Approximately 35 to 60% less vehicles are unable to merge in time for a CACC time gap of 0.9 s compared to a gap of 0.7 s. However, driving at larger time gaps may be undesirable since it causes cut-in lane changes, thereby disengaging the platoon. Concluding, the 'allow yielding' strategy is the most effective solution to the merging problems implied by truck platooning with the 'fixed gaps' strategy.

Discussion of results

There are however several important limitations to the results of this research. The most important limitation is the lack of validation of the adapted simulation model. Although MOTUS was calibrated and validated for the standard model without truck platooning and the adapted model was loosely validated using empirical evidence on motorway traffic in general, there is no empirical data on truck platooning in mixed traffic that is suitable to validate the adapted model. This means that behavioural adaptation of human drivers in the presence of truck platoons remains partly unknown and therefore could not be taken fully into account. Additional research is needed to identify these behavioural adaptations.

Another important limitation is that vehicles in the simulations are simply deleted when they are unable to merge in time. In reality, these vehicles would either stop at the end of the acceleration lane or continue driving on the shoulder lane. At some point, these vehicles would still merge, causing additional disruptions in the traffic flow. These vehicles are not accounted for in the simulations with the 'fixed gaps' strategy. However, the 'allow yielding' strategy revealed that even when all vehicles can merge, the platooning effects found still remain, even though they have become slightly smaller.

Also, when yielding for merging vehicles with the 'allow yielding' strategy, it is assumed that truck drivers take over control instantly when not paying attention. In reality however, a long time may often be needed to successfully complete this transition of control. In that case it is already too late to yield for a merging vehicle. Hence, automatic gap creation is to be preferred to ensure that the truck platoons take action on time. Similarly for the 'allow lane changing' strategy, it may be unlikely that platoon members will actually perform courtesy lane changes in reality if they are driving at a small time gap with their predecessor, since their forward-view is mostly blocked by the predecessor.

Another limitation of the experimental design is the fact that platoon formation is 'on-the-fly', i.e. equipped trucks will only form platoons if they happen to be driving close to each other. This limits the number of platoons that are formed, as reflected by the fact that even when all trucks are equipped, still less than 20% of them actually drive in platoons. If platoons would be planned beforehand, the number of platoons and thereby the effects of truck platooning would be larger.

Conclusions and recommendations

It has been shown that the introduction of truck platoons on the motorway will lead to merging problems at on-ramps. Therefore, truck platooning at motorway on-ramps should only be permitted under certain conditions. A time frame could be implemented, for example allowing truck platooning at on-ramps only during night time. At higher traffic intensities, especially at high on-ramp intensities, truck platooning at on-ramps is not recommended. A policy on whether truck platooning at motorway on-ramps is allowed could be based on the requirement that the number of vehicles unable to merge should not increase compared to the current situation without automated truck platoons. A role for the infrastructure might emerge in providing information to automated vehicles behind the line of sight of the on-board sensors. In that way automated vehicles can be made aware of for instance potential merging issues when approaching an on-ramp, so that truck platoons can already increase their inter-vehicle gaps or so that the arrival times at the on-ramp can be adjusted.

Although a platoon of three trucks causes significantly more merging problems than a platoon of two trucks, a platoon of two trucks still causes them as well. Therefore neither of them is recommended at busy on-ramps. The maximum platoon size allowed on the motorway could be based on the size that is considered acceptable by road users. This is thus a rather flexible limit that may change over time. Similarly, the CACC time gaps researched all result in merging problems and therefore none of them is recommended at busy on-ramps. However, if truck platoons (automatically) yield for merging vehicles, merging problems can be solved and truck platooning at motorway on-ramps becomes safe. Other measures preventing merging issues rather than solving them could be for instance having truck platoons drive in another lane than the right lane. A dedicated lane for platoons could even be considered. Extending acceleration lanes is also an option.

Besides an on-ramp, research on other motorway sections is also recommended, for instance off-ramps, weaving sections or motorways with more than two lanes. A network with multiple of such discontinuities can also be used.

An extension to the modelling framework created in MOTUS could be the more realistic use of trucks with different acceleration and braking capabilities induced by differences in vehicle weight and the implementation of an AD controller that takes into account these differences by adjusting the desired time gap of trucks and using bi-directional communication. Research can then be done on the effects of these differences on the cohesion of the platoons and possible safety issues this might cause for other traffic, especially in situations with lots of variations in speed, such as in congestion shock waves.

Finally, an improvement of car-following and lane change models is desirable to further improve the validity of simulations. The inclusion of more human factors can make the driving behaviour more realistic, which is more important than ever to determine the impacts of automated driving in mixed traffic.

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Important terms and abbreviations

Term	Explanation
Truck platoon	Two or more trucks driving with reduced time gaps of less than 1 second (corresponding with a distance of less than 22 m at 80 km/h) enabled by wireless V2V communication and of which both longitudinal and lateral control is automated (at least SAE level 2).
Conventional vehicle	A vehicle that has no driving automation and is thus manually driven.
Distance gap, time gap, inter-vehicle gap	Space in meters or time in seconds between the vehicle in question and its predecessor in the same lane. In the latter case it is the time between the rear bumper of the predecessor passing a location and the time that the front bumper of the vehicle in question arrives at that location
AD	Automated Driving
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
DSRC	Dedicated Short Range Communication
Wifi-p	Wifi standard especially developed for wireless V2V and V2I communication operating on the 5.9 GHz frequency band
SAE levels	Level of driving automation as determined by SAE International (SAE International 2016)
Microscopic simulation	Simulation in which the behavioural dynamics of each individual vehicle is calculated every time step
MOTUS	Microscopic Open Traffic Simulation (TU Delft 2017)
LMRS	Lane-change Model with Relaxation and Synchronization
ACC	Adaptive Cruise Control
FRACC	Full Range Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
CDG	Constant Distance Gap
CTG	Constant Time Gap
VTG	Variable Time Gap
SDC	Safe Distance Control
OVM	Optimal Velocity Model
IDM, IDM+	Intelligent Driver Model (+)
MPC	Model Predictive Control
TTC	Time to Collision; the time span after which a vehicle will collide with its predecessor if the driving conditions remain unchanged.
TE-TTC, TI-TTC	Time-exposed TTC, time-integrated TTC

1 Introduction

In the future, self-driving trucks will be driving on the motorway as part of a road train by communicating with surrounding trucks, forming a truck platoon. The trucks will be driving very closely behind each other, enabled by automated driving (AD) technology and wireless vehicle-to-vehicle (V2V) communication (Janssen et al. 2015). The trucks will be equipped with systems that take over longitudinal and lateral control from the drivers. They will automatically maintain the correct inter-vehicle gap and speed and perform automatic steering corrections based on the motorway layout and the position of the leader vehicle of the platoon.

1.1 Background of truck platooning

Truck platooning is defined as two or more trucks driving at reduced inter-vehicle gaps (typically less than one second, corresponding with a distance of less than 22 m at 80 km/h) enabled by wireless vehicle-to-vehicle communication and of which both longitudinal and lateral control are automated. As technology advances, truck platooning is becoming more and more an important topic for many stakeholders, as will become clear in the next subsections.

1.1.1 Benefits of truck platooning

The potential benefits of truck platooning are legion. Firstly, truck platooning can reduce transport costs by lowering fuel consumption due to improved aerodynamics from reduced air resistance. All vehicles in a truck platoon experience reduced fuel consumption. For the follower vehicles this varies between 8-13% according to the SARTRE project (Bergenheim et al. 2017). For the leader vehicle the reduction is between 2-8% (Janssen et al. 2015). Secondly, it can eliminate the need for an attentive driver in the follower vehicles or even the presence of a driver. This implies large cost reductions for carriers (Eckhardt 2016). Thirdly, a better usage of truck assets can be realised due to optimisation of driving times and minimisation of idle time. Fourthly, traffic safety increases (Eckhardt 2016) since typically 90% of all traffic accidents are caused by human error (Janssen et al. 2015). Fifthly, congestion and traffic jams may be reduced as road capacities are increased due to reduced inter-vehicle gaps (Eckhardt 2016) and fewer incidents occur and lastly, harmful emissions can decrease when congestion and traffic jams are reduced.

It is expected that truck platooning will be introduced in practice on a large scale earlier than passenger car platooning, making it more urgent to research than passenger car platooning. There are multiple reasons for this. The advantages of platooning can lead to viable business cases for carriers, giving them a strong incentive to install equipment enabling platooning on their trucks. Passenger car drivers usually use their car less than carriers use their trucks, since transportation is their core business. This means that the investment of installing the required technology on trucks has a much shorter return on investment. Moreover, passenger car drivers will only profit from the technology if enough other cars have it installed. Carriers on the other hand can profit immediately as soon as two trucks are equipped. All these factors increase the likelihood that the adoption of platooning technology in trucks will occur sooner than in passenger cars (Janssen et al. 2015).

1.1.2 Urgency to facilitate growing freight traffic

At the same time, economic growth introduces a growing urge to seek new ways to facilitate growing freight streams. In the Netherlands, this challenge is especially urgent because of the expected growth of (container) transshipment. Especially in the port of Rotterdam (Port of Rotterdam 2017a, Port of Rotterdam 2017b) the expected growth is high, even in the most conservative future economic scenario (Planbureau voor de Leefomgeving and Centraal Planbureau 2016). This growth is driven by ever larger (container) ships that can only enter a limited number of ports (JOC Staff 2015). At the same time the road capacity is not expected to increase at the same pace because of a lack of funds (Verrips and Hoen 2016) and public support. Hence, doing nothing is not an option if one wants to prevent ever increasing road congestion and relocation of economic activities to other countries.

1.1.3 Introduction timeline

A lot of research on truck platooning has been performed in recent years, among which are field tests in Europe (Bergenheim et al. 2017) (Eckhardt 2016) (International Automated Transport 2017), Japan

(Tsugawa 2013) and the United States (Institute of Transportation Studies UC Berkeley California 2017). Even more field tests have been planned for the coming years. A phased implementation is regarded crucial for widespread acceptance of platooning technology in practice. It is expected that large-scale implementation of truck platooning in the commercial transportation industry is possible by approximately 2020. By 2023, it should be possible to drive cross-border with multi-brand platoons in Europe without needing any specific exemptions (European Automobile Manufacturers Association (ACEA) 2017). The level of automation of platooning is expected to be limited to SAE level 2 or 3 (SAE International 2016). Fully autonomous trucks will only come later. Higher levels of automation (SAE level 4 or 5) are not expected before 2030 (Janssen et al. 2015). The expected timeline is visualized in Figure 1.1.

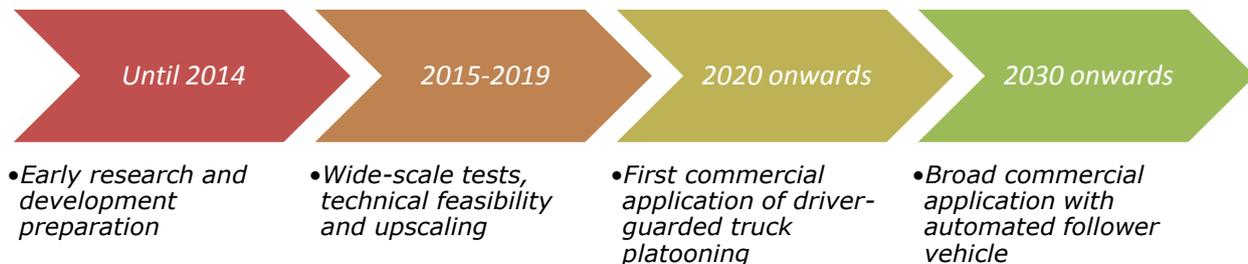


Figure 1.1: Truck platooning introduction timeline (adapted from (Janssen et al. 2015)).

This timeline is highly dependent on political support, innovation funding, technological advance and public acceptance. The greatest threats to the feasibility of this timeline are expected to be the required changes to European and Dutch legislation. The legislation with regard to driving and resting times and the digital tachograph are the most important ones. Another threat is the technological difficulty of ensuring robust control over the platoon under all circumstances (Janssen et al. 2015). Therefore, in the beginning truck platooning will likely be limited to fair weather and only on (motorway) stretches with detailed signage and lane markings (Shladover 2016). There is thus still a lot of uncertainty in the time line.

1.2 Problem definition

As automated vehicles on public roads become more common, road authorities have to consider action to facilitate and regulate their introduction. Because the complexity of traffic dynamics on motorways is relatively low, motorways will be the first type of road where automated driving will be introduced. Moreover, given the financial advantages for carriers, truck platooning on motorways might well become one of the first large-scale applications of automated driving.

Before truck platooning can be introduced, platooning technologies will have to prove themselves safe and reliable. A main challenge lies in the largely unknown effects of the introduction of automated vehicles on mixed (conventional and automated) traffic and the nonconformity in the effects that have been researched (Calvert et al. 2016). The motorway merging behaviour of human drivers in the presence of truck platoons is still largely unknown. Similarly, the desired behaviour of a truck platoon in such a situation is also still largely unknown. When truck platooning on the motorway is introduced, safety issues such as crashes or merging problems can occur when human drivers want to merge on the motorway at an on-ramp if the right lane is (partially) blocked by a truck platoon. Moreover, traffic performance issues such as a breakdown of traffic can occur due to unexpected braking manoeuvres, resulting in additional traffic jams. A (temporary) decrease in traffic performance may occur if truck platoons are unable to perform at the same overall level as human drivers, which might not be accepted by road authorities if this drop in performance lasts too long.

Research to identify and quantify the traffic performance and safety effects of truck platooning on the motorway at on-ramps is thus necessary before deployment in practice. This can be done by modelling driving behaviour of both truck platoons and conventional vehicles in mixed traffic on the motorway. Knowledge about this driving behaviour has to be obtained and translated into algorithms that are used in a traffic simulation model.

1.3 Research goals

The main goal of this research is to **gain insight into the impacts of truck platooning on traffic performance and safety at motorway on-ramps in mixed traffic**. This is done by determining what these traffic performance and safety effects of truck platooning on the motorway are in the situation of conventional vehicles merging at an on-ramp for different platooning strategies and platoon configurations. Platooning strategies can, for example, differ in inter-vehicle gap-keeping policies. Platoon configurations can, for example, differ in platoon sizes and desired inter-vehicle gaps.

1.3.1 Main research question

To get more insight into the traffic performance and safety effects of truck platooning at motorway on-ramps in mixed traffic, this study therefore tries to answer the following research question:

What are the traffic performance and safety effects of truck platooning on the motorway in the situation of conventional vehicles merging at an on-ramp for different platooning strategies and platoon configurations?

1.3.2 Sub questions

To be able to answer the main research question, several sub questions need to be answered. Sub-questions are formulated on two levels. The upper level sub questions cover the different research phases of this study, while the lower level sub questions are more detailed questions that answer a part of the upper level questions. A detailed description of the research approach that tries to explain the way in which all these questions are answered is given in section 1.4. The sub questions are:

- *How can the driving behaviour of truck platoons at motorway on-ramps be modelled?*
 - What does existing literature teach us on modelling longitudinal truck platoon driving behaviour on the motorway (near an on-ramp)?
 - How can the limitations of this modelling be mitigated if these limitations exist?
- *How can human driving behaviour at motorway on-ramps in the presence of truck platoons be modelled?*
 - What does existing research literature teach us on human driving behaviour on the motorway at on-ramps?
 - What do the behavioural models of traffic simulation software tools teach us on human driving behaviour on the motorway at on-ramps?
 - How does the human merging behaviour on the motorway at on-ramps change when there is a truck platoon in the rightmost lane?
- *Which traffic simulation software tools are suitable to simulate truck platooning at motorway on-ramps in mixed traffic?*
 - What traffic simulation software tools exist that are able to model truck platoon driving behaviour in merging conditions with conventional vehicles or can be adapted to perform such modelling?
 - Which traffic simulation software tool is best suitable for this purpose with regard to the accuracy of the modelling, adaptability, availability, complexity, possibilities to generate the desired output and access to support?
- *How can truck platooning be captured in the simulation model?*
 - How can longitudinal truck platoon driving behaviour at motorway on-ramps be incorporated in the simulation model?
 - How can behavioural adaptations of human drivers be captured in the simulation model?
 - How can the adapted simulation model be calibrated and validated?
- *How can the traffic performance and safety of different platooning strategies and platoon configurations be evaluated using simulation?*
 - What road network is feasible to apply in the simulations?
 - Which traffic intensities are feasible to apply in the simulations?
 - Which penetration rates of equipped trucks are feasible to apply in the simulations?
 - What platooning strategies and platoon configurations are feasible to apply in the simulations?

- What simulation scenarios should be researched to capture the effects of all feasible truck platooning strategies and configurations on traffic performance and safety?
- What performance and safety indicators can be used to quantify and qualify traffic performance and safety effects of truck platooning at motorway on-ramps?
- *What recommendations on platooning strategies and platoon configurations can be made given the simulation results?*
 - What is the traffic performance and safety of the different simulation scenarios?
 - How do the traffic performance and safety of the platooning and the non-platooning scenarios compare?
 - How do the traffic performance and safety of the platooning scenarios mutually compare?

1.4 Research approach

The research is divided in five phases addressing all upper level sub research questions. The five phases are:

- **Literature study**
- **Modelling truck platooning in simulation**
- **Experimental design**
- **Simulation results**
- **Conclusions and recommendations**

The phases may be further divided in multiple steps that address sub questions of the lower level. The products that result from each research phase are also given. An overview of the structure of this research approach can be found in Figure 1.2.

1.4.1 Phase 1: Literature study

Step 1.1: Obtain information on the modelling of driving behaviour of truck platoons.

Automated driving (AD) models are studied to shed light on the driving behaviour of automated truck platoons. The research is limited to longitudinal driving behaviour since automated lane changing is outside the scope of this research. The limitations of the AD models and how these can be mitigated to guarantee plausible driving behaviour are also addressed. The advantages and disadvantages of each model are also addressed.

Step 1.2: Obtain information on the modelling of human driving behaviour at motorway on-ramps.

Existing behavioural models are studied shedding light on the important aspects of the intrinsic algorithms that determine the longitudinal and lateral behaviour. Special attention is paid to how well these models approach reality.

Traffic simulation software tools have integrated models determining the longitudinal and lateral behaviour of vehicles. It is studied how these work and how they differ from each other to determine the suitability for the purpose of modelling merging behaviour at on-ramps.

The ability of the models to model merging behaviour in a realistic way is of large influence on the usability of the simulation results. Therefore the limitations of the models and the extent to which they are able to model actual merging behaviour are reported. The effects that these inaccuracies could have on performance indicators used are addressed and quantified where this is possible.

Step 1.3: Analyse traffic simulation software tools to find out how suitable they are for modelling truck platooning at motorway on-ramps.

In the next step existing traffic simulation software tools are studied to find out the possibility and suitability to use them for the purpose of modelling truck platoons and merging vehicles at motorway on-ramps. Special attention is paid to the ability to adapt the integrated behavioural models to include automated driving as well as to the degree to which the merging behaviour of the integrated behavioural models is realistic. Moreover, the ability to obtain the desirable performance indicators from the simulation output is addressed. The suitability of the simulation tools is compared based on

the performance of the integrated behavioural models, the ability to adapt the models to incorporate AD, the ability to obtain the desired output, complexity of use, availability of the tool and availability of support for using and adapting the model.

Step 1.4: Obtain information on behavioural adaptation of human drivers in the presence of truck platoons.

In order to get an idea of how merging vehicles adapt their merging behaviour when there is a truck platoon in the right lane, several comparable traffic situations are studied. Research on the effects on traffic flow of non-automated truck platoons on busy motorway freight routes with lots of trucks as well as research on the effects of the deployment of longer and heavier vehicles (LHVs) in the Netherlands in recent years is used for this.

Product

The product resulting from this phase is a description of longitudinal driving behaviour models of automated truck platoons, including their limitations and how these can be mitigated. This also results in a motivated selection of suitable AD models to apply in a simulation model. Moreover, this phase results in a description of (modelling of) human merging behaviour on the motorway at on-ramps. Both longitudinal and lateral behaviour models are addressed and the expected behavioural adaptations in the presence of truck platoons is also explained. This also results in a motivated selection of suitable driving behaviour models to apply in a simulation model. Finally, it results in a description of existing traffic simulation software tools including their integrated driving behaviour models, their advantages and disadvantages and a comparison of the tools based on the requirements, resulting in a motivated indication of which tool is best suitable for the purpose of modelling truck platooning at motorway on-ramps.

1.4.2 Phase 2: Modelling truck platooning in simulation

Step 2.1: Choose a simulation model and test the performance of the selected AD models.

The literature study provides information on the suitability of longitudinal and lateral driving behaviour models for human drivers and of longitudinal driving behaviour models for truck platoons. It has also been determined which traffic simulation software tool is best suitable for the purpose of simulating truck platooning at a motorway on-ramp. During this process the ability to obtain the desired output in terms of the performance indicators (see phase 3) is also taken into account. With this information, a choice is made on which simulation tool to use, whereby the incorporated driving behaviour models play an important role. Also, the performance of selected longitudinal AD models is tested for different traffic scenarios to test whether they generate plausible driving behaviour. This results in a motivated choice of the longitudinal AD model.

Step 2.2: Modify the driving behaviour models of the chosen simulation tool to incorporate AD.

The driving behaviour models of the selected simulation tool are then modified to incorporate AD for truck platoons. This is the partial replacement of the internal driver behaviour by user-defined behaviour for one or more vehicle classes. Changes to the human merging behaviour are also made where applicable as indicated by the findings from the literature study concerning behavioural adaptation in the presence of truck platoons. Some basic programming skills have been developed at this stage to be able to make the changes. The adaptations are made such that the desired platooning strategies and platoon configurations can be applied (see the next phase 3).

Step 2.3: Tune the control parameters and validate the simulation set-up.

The parameters of the newly incorporated AD model are now tuned using analysis of the truck platoon driving behaviour observed for simulation test runs. Thereby the model is tuned to act like a human driver, with a smooth acceleration response. Its ability to prevent collisions is also a main determinant for the tuning. Moreover, the simulation set-up is validated by comparing performance indicators from simulation test runs with empirical data. The test runs use the scenario constants and variables from the next phase 3.

Product

The product resulting from this phase is a motivated choice of the AD model to be applied in the chosen simulation tool, a simulation model that incorporates the possibility of truck platooning and takes into account changes to the human driving behaviour in the presence of truck platoons and a tuned AD model that is incorporated in the simulation model as well as a validated simulation environment.

1.4.3 Phase 3: Experimental design

Step 3.1: Determine the simulation scenario constants.

The simulations are all performed in the same network and many parameter values also are the same for each scenario. In this step the lay-out of the road network is described and motivated. Relevant platooning parameter values that remain constant for all scenarios are described and motivated as well. The results of this step are also used to perform the simulation test runs and the model modification of the previous phase, as shown by the feedback loop in Figure 1.2.

Step 3.2: Determine the simulation scenario variables.

To be able to quantify the effects of truck platooning for different platooning strategies and platoon configurations, several strategies and configurations are chosen. The choices are based on what is possible and realistic based on the technological possibilities, traffic safety, empirically determined merging behaviour and public and political acceptance. The results of this step are also used to perform the simulation test runs and the model modification of the previous phase, as shown by the feedback loop in Figure 1.2.

Moreover, to be able to quantify the effects of truck platooning strategies and configurations for different traffic intensities, several different traffic intensities are chosen. They each represent a real-life case of a busy motorway freight route in the Netherlands.

Lastly, to be able to quantify the effects of truck platooning strategies and configurations for different numbers of platoons passing the on-ramp per unit of time, several different penetration rates of trucks that are equipped with AD technology are chosen.

By combining all simulation scenario variables, the simulation scenarios are determined.

Step 3.3: Determine how the traffic performance and safety can be determined from simulation data.

To be able to quantify and compare the traffic performance and safety of the different simulation scenarios, performance indicators are chosen. Macro level indicators are used to capture network effects and micro level indicators are used to capture effects on a specific area or (group of) vehicle(s). Both graphical indicators revealing traffic patterns in graphs as well as global values that give one performance value for the entire network are chosen. To be able to determine safety performance, surrogate safety indicators are used that quantify the severity and/or frequency of occurrence of conflicts. The ability to obtain these indicators from the simulations is also taken into account when determining a suitable simulation tool as described in the previous phase.

Step 3.4: Determine how to obtain statistically reliable output.

Once the simulation environment has been prepared, the number of simulation replications necessary to obtain reliable values of the performance indicators is determined. The methodology of how the simulation output data is managed to obtain reliable means and standard deviations is also explained.

Product

The product resulting from this phase is a motivated choice of the road network and the relevant platooning parameter value(s) that remain constant for all simulation scenarios, a motivated choice of simulation scenarios with an overview of all simulation scenario variables, a motivated choice of performance indicators that can quantify the traffic performance and safety of the different simulation scenarios and an explanation of the methodology that is used to obtain reliable values of the performance indicators.

1.4.4 Phase 4: Simulation results

Step 4.2: Compare the performance of the simulation scenarios.

In this step the simulation results are compared for the different scenarios. The effects of truck platooning are described by comparing the platooning scenarios to the corresponding base scenarios. The base scenarios are the scenarios without any platooning that are only different with respect to intensity and composition of traffic on the motorway and the on-ramp. The differences in effects between the different platooning strategies and platoon configurations are also quantified. This is done for all traffic intensities and equipped truck penetration rates.

Product

The product resulting from this phase is an overview of the performance of the simulation scenarios in terms of the performance indicators. This gives an indication of the impacts of truck platooning at motorway on-ramps and of differences between the different platooning strategies and platoon configurations.

1.4.5 Phase 5: Conclusions and recommendations

Step 5.1: Make recommendations for platooning strategies and platoon configurations.

Given the findings from the simulation and evaluation phase, recommendations can be made for platooning strategies and platoon configurations. Different recommendations may be made based on what is considered most important: traffic performance, traffic safety, or a compromise.

Step 5.2: Provide conclusions on the effects of traffic intensities and penetration rates

In addition to the platooning recommendations, conclusions considering the effects of traffic intensity and equipped truck penetration rate are also given. This gives insight into possible capacity effects of truck platooning as well as limitations considering the merging ability of vehicles at the on-ramp.

Step 5.3: Discuss the limitations of the findings

The research is based on the modelling of driving behaviour, which is always an approximation of reality. Limited availability of information might also impose limitations to the findings. Moreover, the scope of the research is limited, meaning that truck platooning might bring along other problems that are not noticed in this research. All of these limitations are discussed in this step, including a discussion on the severity of the consequences of these limitations.

Step 5.4: Reflect on the conduction of the research

A brief reflection on the conduction of the research is also given. It addresses the difficulties encountered and how problems were solved.

Step 5.5: Make recommendations for practice and for further research

Finally, given the limitations discussed in the previous step, recommendations for practice and for further research can be made. These include suggestions on the improvement of the modelling of the driving behaviour and for empirical studies to obtain more information on interaction of conventional vehicles and truck platoons. Recommendations for other traffic networks are also made.

Product

The product resulting from this phase are conclusions and recommendations on the findings from the simulations. This includes recommendations for platooning strategies and platoon configurations, conclusions on traffic intensity and equipped truck penetration rate effects, a discussion on the limitations of the findings, a reflection on the conduction of the research and recommendations for practice and for further research.

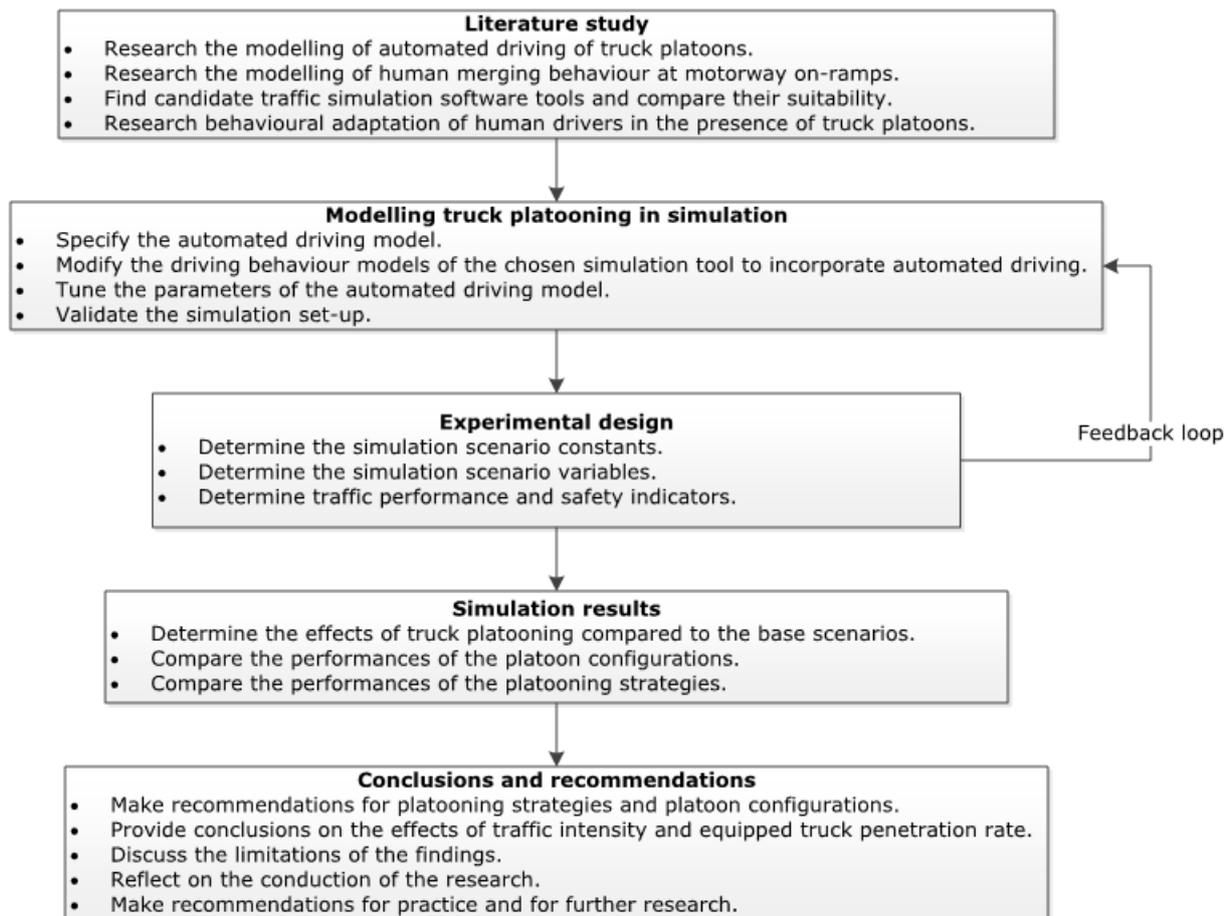


Figure 1.2: Flow chart of the steps of the research.

1.5 Research scope

The scope of this research is bounded in multiple ways:

- Road network: only an on-ramp merging scenario on a two-lane motorway is considered. Other discontinuities are left out of consideration.
- Platoon configuration: the number of trucks in the platoon will have a maximum of three.
- Platoon driving behaviour: the modelling of truck platoon driving behaviour is limited to longitudinal behaviour.
- Truck characteristics: all platoon members in a truck platoon are assumed to have the same acceleration and braking capabilities. Platoon cohesion and safety issues caused by differences in vehicle weight and braking power are thus not considered.
- Automated vehicles: the truck platoon itself is considered as the only automated entity on the road. All other vehicles are assumed to be conventional vehicles.
- Communication: only V2V communication between the trucks is considered, no V2I communication.
- Platooning effects: only traffic performance and safety effects are considered, fuel saving effects are left out of consideration.

1.6 Main contributions

This research intends to help to facilitate and regulate the introduction of automated truck platoons on the motorway in the Netherlands and abroad and to shed some light on the challenges related to this introduction for road authorities and other stakeholders. It tries to do so by providing:

- A simulation environment that can successfully simulate and evaluate truck platoon driving strategies and configurations in the situation of passing a motorway on-ramp.

- New insights into the traffic performance and safety effects of truck platooning on the motorway at on-ramps in relation to truck platoon driving strategies and platoon configurations.

1.7 Report outline

This thesis report is split into five parts that correspond to the five phases of the research approach. An overview of the chapters in relation to the research approach is given in Figure 1.3. Chapter 2 concerns the literature study, consisting of three parts: research on the modelling of truck platoon automated driving behaviour, research on the modelling of human driving behaviour and the suitability of several simulation software tools and research on behavioural adaptation of drivers in the presence of truck platoons. Chapter 3 concerns implementing the desired (automated) driving behaviour in the simulation model and validating and tweaking its performance. Chapter 4 defines the simulation scenarios and performance indicators that will be applied. There is a feedback loop to Chapter 3 because the simulation scenario constants and variables are applied in simulation test runs to check the validity of the model and for programming the right platooning strategies in the model. Also, the choice of simulation tool depends on the ability to obtain the desired performance indicators. Next, Chapter 5 gives an explanation on the simulation results. Finally, conclusions are drawn, the limitations discussed, a reflection given and recommendations made in Chapter 6.

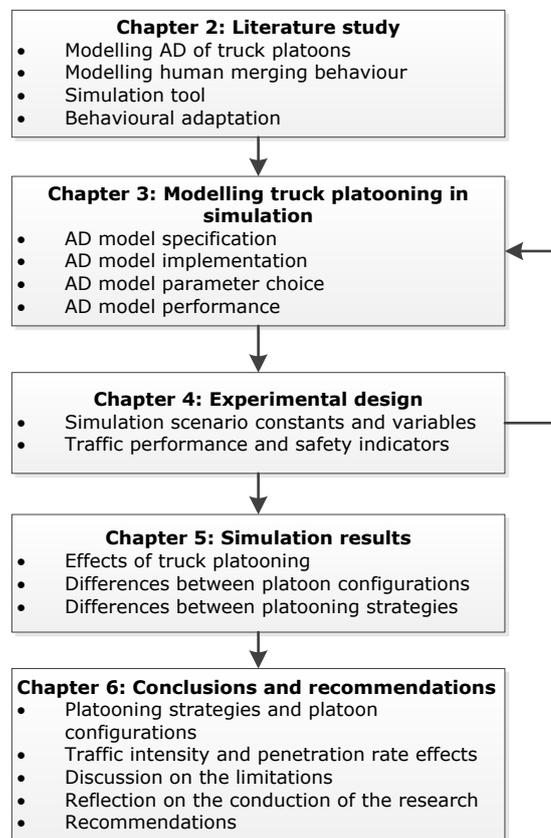


Figure 1.3: Thesis report outline.

2 Literature study

In this chapter a literature study is conducted in order to be able to model truck platoons and conventional vehicles in mixed traffic in simulation. It identifies what has already been researched on modelling this and determines the suitability of the different ways in which this driving behaviour can be modelled. It also aims to identify the knowledge gaps on truck platooning in mixed traffic and the limitations of the current models, so that the limitations of the validity of the simulations can be determined and mitigated. Special attention is paid to behavioural adaptation of human drivers in the presence of truck platoons.

In section 2.1, the modelling of longitudinal automated driving of truck platoons is elaborated on. This includes the controller frameworks of such automated driving. In section 2.2, simulation of human driving behaviour is explored. First, both existing longitudinal and lateral driving behaviour models are dealt with. Different traffic simulation platforms using these models are also considered to get an overview of which driving behaviour models are used by which simulation platform. The suitability of the simulation platforms for modelling on-ramp merging behaviour and truck platooning is thereby determined using performance criteria. In this way a simulation platform is chosen. Research findings on behavioural adaptation of human drivers in the presence of truck platoons is dealt with in section 2.3 to be able to take into account their impact on traffic flow and safety and to identify and mitigate possible shortcomings of the simulations. Finally, the conclusions of the literature study are drawn in section 2.4.

2.1 Modelling longitudinal automated driving of truck platoons

To be able to model truck platoons in simulation, it is necessary to know how such automated driving can be implemented in simulation platforms. Therefore a literature study on the modelling of longitudinal automated driving of truck platoons is conducted. First, the required technology for automated and cooperative driving is briefly described in section 2.1.1. Next, the system allowing automation of the longitudinal driving of platoons is discussed in section 2.1.2. Multiple variants of this system are discussed in sections 2.1.3 and 2.1.4. Subsequently, several variants of theoretical frameworks describing this automated driving as constructed by previous studies are presented in section 2.1.5. A summarising overview of the characteristics of each framework is also given. The limitations and possible solutions to these limitations of the frameworks are discussed in section 2.1.6 and 2.1.7 respectively. Finally, conclusions on modelling truck platooning are given in section 2.1.8.

2.1.1 AD and V2V communication technology

Automated vehicles need Automated Driving (AD) technology to be able to drive by themselves and vehicle-to-vehicle (V2V) communication technology to share information with surrounding vehicles.

AD technology consists of robotic systems that sense the environment using a combination of sensors, among which are often lidar (light detection and ranging), radar and cameras. The sensors can make up for each other's weaknesses and provide redundancy. The quality and unambiguity of the lineage as well as the traffic signs is thereby crucial to guarantee that the sensors detect the necessary objects. This makes the quality and unambiguity crucial in the design of roads (Loon 2016, Loon 2017).

For localisation GPS and an inertial navigation system (INS) are possible. If GPS fails, INS can then take over. The INS can use accelerometers (motion sensors) and gyroscopes (rotation sensors) to help the vehicle orientate while the GPS does not function.

For wireless communication, Wifi-p is used. It allows data exchange between vehicles and between vehicles and the infrastructure. It operates on the 5.9 GHz frequency band (Janssen et al. 2015).

2.1.2 (Cooperative) Adaptive Cruise Control

Longitudinal driving behaviour can be automated using a so-called Adaptive Cruise Control (ACC) system. This is a system that automatically maintains a user-defined speed, similar to regular cruise control, and at the same time automatically accelerates and decelerates to maintain the desired gap with the predecessor.

ACC is however primarily meant as a comfort system and thus relatively large gaps are used. The standardised minimum is a 1 s time gap. If this time gap is decreased well below 1 s, there is an expected increase in traffic throughput. However, it has been shown that ACC amplifies disturbances in upstream direction if small time gaps are applied. These disturbances may for example be caused by speed variations of the first vehicle in a string of vehicles. So-called 'ghost traffic jams' may occur, which negatively influences throughput and possibly safety. To prevent this, string-stable behaviour, i.e. the attenuation of disturbances in upstream direction is necessary for the design of automatic distance control systems. These are needed to allow safe driving at time gaps well below 1 s. A system that is able to achieve this is Cooperative Adaptive Cruise Control (CACC) (Ploeg et al. 2011).

In addition to the functionality of an ACC system, a CACC system adds communication (hence cooperative) with the preceding vehicle(s) that also have the system. This can meet the requirement of string-stable behaviour by providing real-time information of the preceding vehicle. This complements the information obtained by the ACC sensors and allows driving at reduced inter-vehicle time gaps as disturbances in the platoon can be reacted to earlier due to reduced reaction times.

A large number of (C)ACC variants exist. They are different with respect to the gap regulation strategy used. For CACC, they can also differ with respect to the communication lay-out.

2.1.3 CACC communication variants

Communication between a variety of other vehicles can take place. Relevant vehicles include the platoon leader and the (immediate) predecessors and possibly the immediate follower. Any other vehicle within range may also be included. Moreover, a variety of information can be transmitted. The communicated data should at least include speed, location, acceleration/deceleration, intentions (planned changes in speed and acceleration/deceleration) and performance limitations (related to the vehicle's dynamic capabilities). CACC variants with vehicle to infrastructure communication also exist, but these are outside the scope of this research. If there is no communication with other vehicles, CACC is reduced to ACC.

The most basic and most used form of CACC is the form where the vehicle in question only receives information from its immediate predecessor (Ploeg et al. 2014). More advanced forms of CACC add communication with vehicles further downstream. This is obviously only applicable when there are more than two vehicles in the platoon. The advantage of this more advanced form is that communication from the leader to the followers is not increasingly delayed as the vehicle in question is further in the back of the platoon, since all vehicles directly receive the information from the platoon leader. This improves the stability of the platoon (Shladover et al. 2015). It is also possible that a platoon member communicates with its follower (backwards-looking) or in both directions (bi-directional). This allows using information from upstream vehicles to adjust the driving behaviour of vehicles further downstream, potentially improving the platoon cohesion (Zegers et al. 2017).

2.1.4 ACC gap regulation strategies

Several inter-vehicle gap regulation strategies are distinguished for (C)ACC platoons, of which the most common ones are discussed in the next sections. A schematic illustration of the strategies with the explaining symbols is given in Figure 2.1, which is an ACC controller.

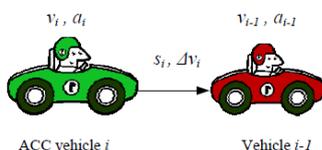


Figure 2.1: ACC controller (Wang 2014).

Constant distance gap

The first one is a constant distance gap (CDG) strategy. With this strategy, the distance gap between the vehicles remains constant (like with a mechanical link). This can only be achieved when all platoon members communicate directly with the platoon leader. This strategy allows a maximum reduction of aerodynamic drag and has the highest potential influence on road capacity (Shladover et al. 2015). However, it imposes the highest safety risks as interruptions of the communication have more serious consequences and sudden hard braking by the platoon leader can lead to collisions, depending on the

distance gap maintained. Therefore it is necessary to maintain large gaps in front of the platoon to reduce the likelihood that the platoon leader needs to perform such braking manoeuvres. Because the algorithm does not guarantee collision free driving and the desired gap is not related to vehicle speed, a CDG strategy does not lead to plausible car-following behaviour and thus user acceptance of this strategy is very low. The control algorithm of the CDG strategy is given and explained in **Appendix A**.

Constant time gap

The second strategy is a constant time gap (CTG) strategy. This represents most closely the way in which human drivers act. Commercially available ACC systems follow this strategy (Shladover et al. 2015). It generates the most plausible driving behaviour with respect to string stability and safety and is in line with the most practical, acceptable and common application of ACC as well as with what is most likely applied by OEMs (Ioannou and Chien 1993, Naus et al. 2010). The distance gap between the vehicles in the platoon is directly proportional to the speed of the platoon, plus a safety distance for standstill situations. This distance is often taken as 1 or 2 m for passenger cars and 3 m for trucks (van Arem et al. 2006), (Schakel et al. 2012). Although this strategy implies reduced aerodynamic drag and road capacity benefits compared to the CDG strategy, the safety risks are lower. Sudden braking by the platoon leader will not lead to collisions if the time gap is chosen properly. However, approaching a standstill vehicle with high speeds can result in collisions. In practice, the ACC system with CTG strategy is therefore switched off in such safety-critical conditions as well as in dense traffic conditions (Wang 2014). User acceptance of this strategy is therefore fair. Because the distance gap is temporarily increased during acceleration and decreased during deceleration, the acceleration variability of the follower vehicles is reduced. This smoothens traffic flow and can enhance energy saving (Omae et al. 2013). The CTG strategy can be extended by adding information from multiple predecessors to achieve CACC functionality. According to (Wang 2014), the algorithm for the CTG strategy is as in **equation (2.1) and (2.2)**.

$$a_{i,t} = k_s (s_{i,t} - s_{i,des,t}) + k_{\Delta v} (v_{i-1,t} - v_{i,t}) \quad (2.1)$$

with

$$s_{i,des,t} = v_{i,t} t_{des} + s_0 \quad (2.2)$$

Where:

$a_{i,t}$: desired acceleration of vehicle i at time t [m/s²]

$k_s, k_{\Delta v}$: control parameters for the gap error and the speed error respectively

$s_{i,t}$: distance gap of vehicle i with vehicle $i-1$ at time t [m]

$s_{i,des,t}$: desired distance gap of vehicle i with vehicle $i-1$ at time t [m]

$v_{i-1,t}, v_{i,t}$: speed of vehicle $i-1$ and vehicle i at time t respectively [m/s]

t_{des} : desired time gap [s]

s_0 : minimum distance gap at standstill [m]

Desired ACC time gap setting

Frequently used time gaps for ACC controllers vary between 0.9 and 2.5 seconds for passenger cars (Fountoulakis et al. 2017). A value of 1.8 s corresponds to the minimum technical standard for trucks (Omae et al. 2013). The ACC gap should be chosen such that it does not deviate too much from the average gap maintained by human drivers and is acceptable for the users. In that way the equipped trucks will allow vehicles to merge in front of the platoon.

A value of 2 s normally corresponds to the safe gap for manual driving of passenger vehicles (Wang et al. 2017). However, assuming a non-congested lane capacity of approximately 2200 vehicles/h at approximately 90 km/h (Henkens and Tamminga 2015) and an average vehicle length of 4.5 m, the average desired time gap for manual driving is approximately 1.46 s ($\approx 3600/2200 \cdot 4.5/(90/3.6)$) for passenger vehicles in practice. As trucks are accounted for as more than one passenger car using a passenger car equivalent (pce) value for a motorway for trucks of 2 (Henkens and Tamminga 2015, Rijkswaterstaat 2015) and given a standard truck-trailer combination length of 16.5 m, the average time gap of manually driving trucks could thus be estimated at 2.61 s ($\approx 3600/2200 \cdot 2 \cdot 16.5/(90/3.6)$) at the same speed. This value however depends heavily on the pce value used. Other research

however suggests an average gap of manual passenger cars of only 1.2 s (Schakel et al. 2010), resulting in an average of approximately 2.1 s for trucks at 90 km/h. (SWOV 2013) notes that the average gap observed for trucks is approximately 1.3 s at speeds from about 90 km/h. In short, the gap depends heavily on the source of information used.

The user acceptance of small time gaps has been verified by tests of acceptance by drivers from the general public (Milanes et al. 2014).

Given these considerations and findings, a reasonable ACC gap could be 1.5 s. This is much lower than the values calculated using the lane capacity, but those values have a high uncertainty because the pce value is disputable. In practice the gaps maintained by trucks are much more comparable to those of passenger cars. Also, user acceptance indicates the possibility of lower values. The proposed value lies in between the average value observed for passenger cars and the value calculated from the capacity, while not deviating too much from the current technical standard for trucks (Omae et al. 2013). This allows researching truck platooning to its full potential while still maintaining an acceptable and safe gap with predecessors and enabling them to merge in front of the platoon.

Variable time gap

The third strategy is a variable time gap (VTG) strategy. With this strategy, the desired gap is variable instead of linear proportional to the speed. This strategy has potentials to improve traffic flow stability according to (Wang 2014). A quadratic distance gap controller is possible. Similar to the CTG strategy, the VTG strategy can be extended by adding information from multiple predecessors to achieve CACC functionality. The control algorithm of the VTG strategy is given and explained in **Appendix A**.

Safe distance control

The fourth strategy is a safe distance control (SDC) strategy. This strategy is similar to the safe distance car-following model by (Gipps 1981). This control strategy uses two different functions to determine the desired acceleration. The choice which function is used depends on a safety gap definition. The actual gap should not be smaller than this safety gap. At standstill, it is assumed that the gap is not smaller than a predefined threshold (the minimum gap). The control algorithm of the SDC strategy is given and explained in **Appendix A**.

Based on IDM and OVM

Yet another strategy is a strategy based on existing car-following models. Two models can be used: the Intelligent Driver Model (IDM) and the Optimal Velocity Model (OVM). The IDM resembles human car-following behaviour and application in ACC equipped vehicles resulted in high user acceptance. Different from the IDM, the OVM cannot guarantee collision-free behaviour. This implies that if the OVM is used, the ACC system has to be switched off in critical conditions. The OVM does not generate plausible car-following behaviour (Wang 2014). The control algorithms of the IDM and OVM strategies are given and explained in **Appendix A**.

Model predictive control approach

The final gap regulation strategy that will be discussed is a model predictive control (MPC) approach, also called receding horizon control. This approach uses a linear quadratic regulator (LQR) for longitudinal control. It is relatively flexible in the sense that it can deal with multiple design criteria and constraints on state and control variables. In the MPC approach the desired acceleration is calculated with a linear feedback control law of the state. This type of controller aims at minimising the deviation from the desired gap, predecessor speed, acceleration and jerk. It also aims at minimising the deviation from a human desired acceleration that is calculated using the Helly model (see also section 2.2.1) (Wang et al. 2016).

When two or more vehicles form a platoon, the MPC approach makes sure that the platooning vehicles use the most recent state and predicted control information of surrounding cooperative vehicles by using V2V communication. This information is used for decision-making on driving behaviour. A joint cost function is defined that considers the situation of a vehicle itself and its follower. The goal is to minimize this joint cost function by using the information gained from the V2V communication. Even when the follower vehicle is not automated, the joint cost function is still used by predicting the behaviour of the follower.

The most important characteristics of the gap regulation strategies and possible communication variants that can optionally be used by the strategies to go from ACC to CACC functionality are given in Table 2.1. Since no applications in research on some of the strategies with V2V communication added has been found, the communication options of some of the strategies remain unknown.

Table 2.1: Overview of the most important characteristics of the gap regulation strategies with communication variants.

Gap regulation strategies	Car-following behaviour	Collision risk	Gap sizes	Driver acceptance	Optional: communication	
					Communication with	Communication failure risks
CDG	Like a mechanical link	Large gaps in front of platoon necessary	Very small	Low	Platoon leader	Very high
CTG	Smoothens	High in critical conditions	Linear function of speed	Medium	(Multiple) predecessor(s)	Medium
VTG	Potential to improve traffic stability	Unknown	Quadratic function of speed	High	(Multiple) predecessor(s)	Medium
SDC	Like CTG, but more safety	Collision free	Fixed safety gap	Unknown	Possibilities unknown	Unknown
IDM	Resembles humans, non-linear	Collision free	Linear function of (relative) speed	High	Possibilities unknown	Unknown
OVM	Not plausible, non-linear	Very high in critical conditions	Speed is function of gap size	Low	Possibilities unknown	Unknown
MPC	Aimed at minimising joint cost, non-linear	High in critical conditions	Determined using state prediction	Medium	(Multiple) predecessor(s), follower	Medium

2.1.5 (C)ACC controller frameworks

Several theoretical frameworks describing CACC functionality have been proposed in previous studies. These entail variants with different communication lay-outs. All theoretical CACC frameworks found use the CTG strategy as gap regulation strategy. The possible variants will be discussed in the next sections. The platoon leader will use ACC to interact with its predecessor since the platoon leader cannot communicate with its predecessor. The ACC controller framework is therefore first explored.

ACC controller framework

ACC algorithms usually have two driving modes: cruising mode and car-following mode. In cruising mode, a desired speed is maintained, see **equation (2.3)**. This describes regular cruise control functionality. In car-following mode, a desired gap with the predecessor is maintained, see **equation (2.4)**. This situation is displayed in Figure 2.1. The system switches between the two modes based on for example a distance gap threshold. According to (Wang 2014), in previous studies this threshold was for example a fixed distance of 100 m or a fixed distance depending on the range of the forward-looking sensor. Another approach used is not to define a fixed distance threshold to switch between the modes, but rather to compare the desired accelerations calculated by both modes and choose the smallest one as in **equation (2.5)**. This approach ensures that platoon followers will not accelerate to

a speed that is higher than their desired speed. A schematic illustration of the ACC controller with the explaining symbols is given in Figure 2.1.

$$a_{i,t}^{\text{cruising}} = k_v (v_{des} - v_{i,t}) \quad (2.3)$$

Where:

$a_{i,t}^{\text{cruising}}$: desired acceleration of vehicle i at time t for the cruising mode [m/s²]

k_v : control parameter for the speed error

v_{des} : desired speed of vehicle i

$$a_{i,t}^{\text{car-following}} = f(s_{i,t}, \Delta v_{i,t}, v_{i,t}) \quad (2.4)$$

Where:

$a_{i,t}^{\text{car-following}}$: desired acceleration of vehicle i at time t for the car-following mode [m/s²]

$$a_{i,t} = \min(a_{i,t}^{\text{cruising}}, a_{i,t}^{\text{car-following}}) \quad (2.5)$$

According to literature, the value of k_v is generally set to 0.3-0.4 s⁻¹ (Xiao et al. 2017). The transition process between cruising mode and car-following mode should be designed carefully to ensure a smooth transition between the two. The equation for the desired acceleration as calculated in car-following mode depends on the communication lay-out and the gap regulation strategy used. In the following sections several variants of this equation are presented.

Multi-anticipative CACC controller frameworks

Multi-anticipative CACC controller frameworks are those for which the vehicle in question communicates with one or more CACC predecessors, so with one or more vehicles in front of it. Most frameworks are of this kind. In earlier research, numerous multi-anticipative CACC controllers have been proposed. They differ in the number of predecessors that can be taken into account by the vehicle in question. Moreover, they also differ in whether they take into account the vehicle's jerk. A schematic illustration of the multi-anticipative CACC controller with the explaining symbols is given in Figure 2.2.

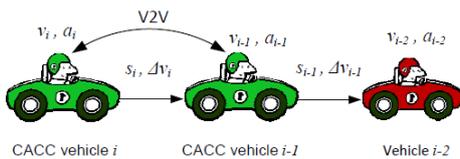


Figure 2.2: Multi-anticipative CACC controller (Wang 2014).

Multiple CACC predecessors

(Wilmink et al. 2007) as well as (Wang 2014) (based on the work of (Wilmink et al. 2007)) both present a multi-anticipative CACC controller framework. This controller can take into account multiple CACC predecessors.

(C)ACC algorithm

The acceleration of the platoon is determined by a function based on a linear combination of the deviation of the current gap from the desired gap, the relative speed with the predecessor and the sum of the relative speed of predecessors further downstream.

All three terms in the CACC function are multiplied with control parameters to be set empirically. The values of these parameters and the time interval after which the desired acceleration is continuously updated in simulation are closely related. The general ACC/CACC algorithm in discrete time is given by **equation (2.6)**.

$$a_{i,t} = k_s (s_{i,t} - s_{i,des,t}) + k_{\Delta v} (v_{i-1,t} - v_{i,t}) + \sum_{k=i-n+1}^{i-1} [\alpha_k (s_{k,t} - s_{k,des,t}) + \beta_k (v_{k-1,t} - v_{k,t})] \quad (2.6)$$

Where:

n : number of vehicles downstream of the CACC vehicle (≥ 2) ($n=2$ in Figure 2.2) [-]

α_k, β_k : control parameters of the gap and speed error of vehicles k respectively

$s_{i,des,t}$ is calculated according to **equation (2.2)**. The first two terms on the right hand side of **equation (2.6)** are equal to the CTG strategy. This is the adaptive part of a CACC controller. The third term incorporates the relative speeds to the vehicles further in front of the vehicle in question. It does so by taking the average relative speeds of all vehicles further in front (so excluding only the vehicle directly in front) of the vehicle in question, once again multiplied by a control/sensitivity parameter. This term implies that the CACC vehicles tend to accelerate when their CACC predecessors are driving with a larger gap than desired or with a lower speed than their predecessor and vice versa. By taking the average, the relative speed of the vehicle directly in front accounts for the same weight as the vehicles further in front. In this way speed adjustments of the vehicle directly in front are more important than those of the vehicles further in front. A small disturbance somewhere in the platoon will therefore not directly result in the entire platoon being disturbed. This is the cooperative or multi-anticipation term of the CACC controller, enabled by V2V communication.

By adjusting the control/sensitivity parameters, the reaction of the vehicle to a change in gap or relative speed can be adjusted. Higher values will result in a faster acceleration or deceleration.

Single CACC predecessor

In (Deng 2016) another multi-anticipative CACC controller framework is proposed. A similar controller was proposed by (van Arem et al. 2006). This controller can take into account only one CACC predecessor.

(C)ACC algorithm

The acceleration of the platoon is determined by a function based on a linear combination of the deviation of the current gap from the desired gap, the relative speed with the predecessor and the acceleration of the predecessor.

All three terms in the CACC function are multiplied with control parameters to be set empirically. The values of these parameters and the time interval after which the desired acceleration is continuously updated in simulation are closely related. For a truck platoon the general ACC/CACC algorithm in discrete time is given by **equation (2.7)**.

$$a_{i,t} = k_s (s_{i,t} - s_{i,des,t}) + k_{\Delta v} (v_{i-1,t} - v_{i,t}) + k_a a_{i-1,t} \quad (2.7)$$

Where:

k_a : discrete parameter, 0 for ACC and 1 for CACC

$a_{i-1,t}$: desired acceleration of vehicle $i-1$ at time t [m/s^2]

$s_{i,des,t}$ is again calculated according to **equation (2.2)**. In **equation (2.7)**, the first two terms are the same as in **equation (2.1)**, corresponding to the CTG strategy. The last term is the predecessor acceleration term. This term implies that a CACC vehicle will accelerate when its predecessor does so and vice versa.

In this CACC algorithm, the vehicle's speed and position are updated each time interval according to **equation (2.8) and (2.9)**. Using the updated vehicle speed and position, the updated acceleration can be calculated.

$$v_{i,t+1} = v_{i,t} + a_{i,t}\Delta t \quad (2.8)$$

$$x_{i,t+1} = x_{i,t} + v_{i,t}\Delta t + \frac{1}{2}a_{i,t}\Delta t^2 \quad (2.9)$$

Where:

$v_{i,t+1}$: speed of vehicle i at time $t+1$ [m/s]

$x_{i,t+1}$: position of vehicle i at time $t+1$ [m]

Δt : time interval for the acceleration update [s]

In (van Arem et al. 2006) the values of the control parameters were found to be $k_{\Delta v} = 0.58$ and $k_s = 0.1$. Moreover, a t_{des} of 0.5 and 1 s were used for CACC and ACC respectively. The standstill distance s_0 was put at 1 m for passenger cars.

The leader vehicle of the CACC platoon cannot anticipate since its predecessor does not communicate with it. Therefore the platoon leader will have a controller according to the CTG strategy which can be denoted as in **equation (2.10)**.

$$a_{i-1,t} = k_s(s_{i-1,t} - s_{i-1,des,t}) + k_{\Delta v}(v_{i-2,t} - v_{i-1,t}) \quad (2.10)$$

When **equation (2.7)** is rewritten by filling in **equation (2.10)**, it can be seen that **equation (2.7)** is in fact similar to **equation (2.6)** with $n=2$ (as in Figure 2.2).

Single CACC predecessor including jerk

In (Ploeg et al. 2011) and (Bronkhorst 2014) another multi-anticipative CACC controller framework is presented. This controller can also take into account only one CACC predecessor, but also includes the jerk.

(C)ACC algorithm

The acceleration of the platoon is determined by a function based on a linear combination of the deviation of the current gap from the desired gap, the relative speed with the predecessor, the acceleration of the predecessor and the jerk.

All terms in the CACC function are multiplied with control parameters to be set empirically. The values of these parameters and the time interval after which the desired acceleration is continuously updated in simulation are closely related. For a platoon the general ACC/CACC algorithm in discrete time is given by **equation (2.12)**.

The proposed CACC algorithm of this study is presented by formulating the error dynamics. Given the definitions of the time derivatives of the position, speed and acceleration of a vehicle according to **equation (2.11)**, the vehicle model is presented as a state space system in matrix form as in **equation (2.12) and (2.13)**. This equation determines how the errors in relative speed, acceleration and jerk change over time.

$$\begin{pmatrix} \dot{s}_{i,t} \\ \dot{v}_{i,t} \\ \dot{a}_{i,t} \end{pmatrix} = \begin{pmatrix} v_{i-1,t} - v_{i,t} \\ a_{i,t} \\ -\frac{1}{\tau}a_{i,t} + \frac{1}{\tau}u_{i,t} \end{pmatrix} \quad (2.11)$$

$$\begin{pmatrix} \dot{e}_{i,dist,t} \\ \dot{e}_{i,speed,t} \\ \dot{e}_{i,acc,t} \\ \dot{u}_{i,t} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\frac{k_p}{\tau} & -\frac{k_d}{\tau} & -\frac{1+k_{dd}}{\tau} & 0 \\ \frac{k_p}{t_{des}} & \frac{k_d}{t_{des}} & \frac{k_{dd}}{t_{des}} & -\frac{1}{t_{des}} \end{pmatrix} \begin{pmatrix} e_{i,dist,t} \\ e_{i,speed,t} \\ e_{i,acc,t} \\ u_{i,t} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{t_{des}} \end{pmatrix} u_{i-1,t} \quad (2.12)$$

with

$$\begin{pmatrix} e_{i,dist,t} \\ e_{i,speed,t} \\ e_{i,acc,t} \end{pmatrix} = \begin{pmatrix} (x_{i-1,t} - x_{i,t} - l_i) - (v_{i,t} t_{des} + s_0) \\ v_{i-1,t} - v_{i,t} - a_{i,t} t_{des} \\ a_{i-1,t} - a_{i,t} - \dot{a}_{i,t} t_{des} \end{pmatrix} \quad (2.13)$$

Where:

$\dot{s}_{i,t}$, $\dot{v}_{i,t}$, $\dot{a}_{i,t}$: time derivative of the distance gap, speed and acceleration of vehicle i at time t respectively [m/s, m/s², m/s³]

$a_{i,t}$: actual acceleration of vehicle i at time t [m/s²]

$u_{i,t}$: desired acceleration of vehicle i at time t (external input) [m/s²]

τ : time constant (depending on engine dynamics) [s]

$\dot{e}_{i,dist,t}$, $\dot{e}_{i,speed,t}$, $\dot{e}_{i,acc,t}$: time derivative of the distance gap, relative speed and relative acceleration error of vehicle i at time t respectively [m/s, m/s², m/s³]

$\dot{u}_{i,t}$: time derivative of the desired acceleration of vehicle i at time t [m/s³]

$e_{i,dist,t}$, $e_{i,speed,t}$, $e_{i,acc,t}$: distance gap, relative speed and relative acceleration error of vehicle i at time t respectively [m, m/s, m/s²]

k_p , k_d , k_{dd} : control parameters for the relative position, speed and acceleration error respectively

$u_{i-1,t}$: desired acceleration of the predecessor $i-1$ at time t [m/s²]

Different from the other frameworks, this model also incorporates the time derivative of the acceleration, indicating the jerk. At the same time it only incorporates the acceleration of the immediate predecessor and not multiple predecessors. If **equation (2.12)** is rewritten with $u_{i,t}$

explicitly and $k_{dd} = 0$, it can be seen that this CACC controller is in fact the same as that of **equation (2.7)**. The control parameters are set on the basis of speed of response in relation to passenger comfort. In that way it was found that $k_p = 0.2$ and $k_d = 0.7$ are feasible control parameter values.

The value of k_{dd} is set to zero because the feedback of the vehicle's jerk is in practice unfeasible.

Therefore this CACC controller algorithm becomes equal to the algorithm of **equation (2.7)**.

Moreover, this controller also uses the CTG strategy. The additional cooperative term is the term that incorporates the acceleration. This term implies that a CACC vehicle will accelerate when its predecessor does so and vice versa. This framework was applied on a passenger car test fleet during a field test in which the theoretical findings were confirmed (Ploeg et al. 2011).

Constant distance gap strategy

As indicated by **equation (2.6) till (2.13)**, all multi-anticipative CACC controllers incorporate the CTG strategy. A multi-anticipative controller with a CDG is also possible. In that case the follower vehicles do not anticipate the acceleration of the predecessor, but the acceleration of the platoon leader. The platoon leader then communicates the relevant information to all vehicles in the platoon. Because of the disadvantages of the CDG strategy, CACC controllers using a CDG strategy are not further explored in this research.

Backwards-looking CACC controller frameworks

Backwards-looking CACC controller frameworks are those for which the vehicle in question communicates with its CACC follower, so the vehicle behind it. This kind of controller is more uncommon. A schematic illustration of the backwards-looking CACC controller with the explaining symbols is given in Figure 2.3.

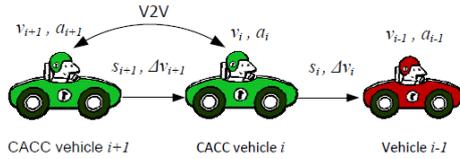


Figure 2.3: Backwards-looking CACC controller (Wang 2014).

According to (Wang 2014), (Nakayama et al. 2002) proposed a controller in which the CACC vehicle does not only anticipate the actions of its predecessors, but also looks backwards to its followers. The desired acceleration is then given by **equation (2.14)**.

$$a_{i,t} = \alpha(v_{opt}(s_{i,t}) + v_B(s_{i+1,t}) - v_{i,t}) \quad (2.14)$$

Where:

α : sensitivity factor

v_{opt} : optimal velocity of vehicle i at time t depending on the gap with the predecessor (function of $s_{i,t}$) [m/s]

v_B : optimal velocity of vehicle i at time t depending on the gap with the follower (function of $s_{i+1,t}$) [m/s]

v_B is a decreasing function of the distance gap, which implies that when the gap behind the CACC vehicle becomes smaller, it tends to increase its speed to create more space for the follower.

Desired CACC time gap setting

For CACC, frequently suggested time gaps for CACC may vary between 0.3 and 1.5 s (Ploeg et al. 2011) (Nieuwenhuijze et al. 2012) (Gouy et al. 2014) depending on the controller used and the communication delay. In practice, CACC gaps should be chosen such that they are large enough to be acceptable for users and politics, but small enough so that the trucks have significant fuel savings and are recognisable as a platoon so that vehicles will not merge in the platoon.

The user acceptance of small time gaps has been verified by tests of acceptance by passenger car drivers from the general public (Milanes et al. 2014). The politically accepted minimum during the EU Truck Platooning Challenge in 2016 was already 0.5 s (BAR Commissie and Rijkswaterstaat 2017). The choice of CACC time gap settings is further explained in section 4.2.2.

Overview of characteristics of the (C)ACC controller frameworks

The most important characteristics of the (C)ACC controller frameworks discussed are given in Table 2.2. It is assumed that the control parameters and desired time gap are chosen such that the platoon is stable, i.e. disturbances are attenuated.

Table 2.2: Overview of the most important characteristics of the (C)ACC controller frameworks.

(C)ACC controller	Gap regulation strategy	Car-following behaviour	Collision risk
Multi-anticipative	CTG		
<ul style="list-style-type: none"> A: Multiple CACC predecessors 		Disturbances highly smoothed (if $n > 2$)	High in critical conditions (but lower than B if $n > 2$)
<ul style="list-style-type: none"> B: Single CACC predecessor 		Disturbances smoothed	High in critical conditions (and higher than A if $n > 2$)
Backwards-looking	OVM	Can only anticipate in upstream direction	High in critical conditions

2.1.6 Limitations of the (C)ACC controller frameworks

The controller frameworks discussed have some disadvantages that limit their applicability. The most important ones are discussed in this section. They emerge from the absence of vehicle capability and comfort constraints, string stability constraints, communication and actuator delay, communication lay-out limitations, platoon size limitations and also the absence of a safety mechanism.

Absence of vehicle capability and comfort constraints

These algorithms generate desired accelerations without considering the vehicle's properties. That means that a calculated desired acceleration could exceed the vehicle's capabilities. The maximum acceleration is bound by the ratio of maximum net force acting upon the vehicle to the mass of the vehicle. The maximum net force thereby is the sum of the maximum engine force, the air resistance, the rolling friction and gravity force. Gravity force is only of interest for non-level road sections. Using reasonable values for the vehicle properties, in (Deng 2016), the maximum acceleration of the follower truck was found to be between 0.13 and 0.2 m/s². This is well within the range of driving comfort, which states a maximum of 2 m/s². Moreover, the maximum deceleration in (Deng 2016) is modelled according to the driving comfort limit, which is -3 m/s². However, these values thus depend on the vehicle capability assumptions.

In addition to these restrictions, vehicle capabilities can vary heavily between trucks. Engine power to weight ratios can differ a lot depending on the load carried by the trucks. This restricts acceleration and deceleration capabilities. Disturbances due to gear shifting, by wind and by road inclination can also have a large effect on these capabilities. Furthermore, the braking system that often consists of service brakes, an engine brake and a transmission retarder play an important role therein.

String stability constraints

When driving at small inter-vehicle time gaps, string-unstable driving behaviour may result. String stability indicates whether oscillations are amplified upstream the traffic flow. A platoon is string stable if sudden changes in the speed of the leader are attenuated by the vehicles upstream the platoon. A common example of string instability is the formation of a traffic jam when there is no apparent bottleneck but there is too much traffic. A braking manoeuvre may result in a shockwave with increased braking upstream a string of vehicles, ultimately resulting in a traffic jam. Considering safety, traffic throughput and comfort, string unstable behaviour is thus highly undesirable (Naus et al. 2010).

Communication and actuator delay

The control algorithms discussed do not consider any actuator delay, but assume that a platoon follower will instantly react to the information on the acceleration behaviour it receives from its predecessor. In reality there will be a communication delay induced by the latency of the data supply plus an actuator delay the in-vehicle systems processing time. The actuator delays are typically caused by the actuators, the engine control unit (ECU) and the electronic braking system (EBS) (Nieuwenhuijze et al. 2012). The total delay is equal to approximately 150 ms to 500 ms, but depends heavily on the in-vehicle systems' properties. (Ploeg et al. 2011) gives values for string-stable time

gaps resulting from a field test with (C)ACC equipped passenger cars. The delay implies that the string stability is negatively affected and that the ideal time gap should be increased to prevent collisions in critical conditions.

Forward-looking communication only

The forward-looking controller frameworks discussed are useful and practical in many applications. However, sometimes it is desirable to have more flexibility in the design of the interaction between vehicles in a platoon. With a forward-looking only controller it is not possible to inform the leader of the performance of the followers. This is especially a disadvantage for truck platoons. The weight of the trucks may greatly differ depending on the load, resulting in different acceleration and speed capabilities. This can lead to an undesired break-up of the platoon if the leader receives no information from the followers (Zegers et al. 2017).

Platoon size limitations

There are several reasons why the number of trucks driving in a platoon must be limited (Shladover et al. 2015). These include safety constraints, vehicle and stability performance limitations and interaction with human drivers.

From a technological perspective, platoon sizes would only be limited by the communication range of the wireless communication devices used. Assuming a form of CACC in which all vehicles require information from the leader vehicle, this limit would be approximately 300 m for 5.9 GHz DSRC. For a form of CACC in which only information from the immediate predecessor is used, the limit would be nearly infinite (Shladover et al. 2015). In both cases the limit is too high to be considered safe. Therefore the limit will need to be determined based on other constraints.

Another constraint to platoon size can be string stability, as described in one of the previous paragraphs. This is only true if the (C)ACC gaps and/or the communication delay are small and large enough respectively so that instability can occur. For CACC systems in which all vehicles receive information from the platoon leader, the stability limit is between 10 and 20 vehicles. For CACC systems in which vehicles only receive information from their immediate predecessor, this limit will be lower. The stability constraint can be different depending on the gap regulation strategy used (Shladover et al. 2015). String stability constraints are not very relevant for platoons with only few vehicles because instability has little chance to grow in upstream direction.

The most serious limitation of platoon size is expected to arise from the need to provide sufficient gaps to enable other vehicles to change lanes. This is especially relevant when the gaps maintained by the platoon members are small enough to prevent most cut-in lane changes (Shladover et al. 2015).

Another important limitation is the degree to which drivers find a certain platoon size acceptable. Obviously, drivers will not be in favour of merging next to a platoon the size of multiple trucks. This user acceptance of drivers might increase over time as drivers become more familiar with automated truck platoons. Verification with Rijkswaterstaat employees as well as current field test plans in the EU indicate that a maximum of three trucks per platoon is likely to be considered acceptable within the first years after deployment (Cornelissen et al. 2017) (European Automobile Manufacturers Association (ACEA) 2017). This is also in line with the EU Truck Platooning Challenge, where the maximum platoon size was three vehicles (BAR Commissie and Rijkswaterstaat 2017). Politics follows to a large extent the public opinion, although it is in favour of developments that might lead to financial advantages and is willing to provide room for experiments (Vermijs 2017). Only after truck platoons have proven to be sufficiently safe according to road users and politicians, larger platoon sizes become feasible.

Absence of a safety mechanism

A large limitation of the (C)ACC frameworks discussed is that none of them has a proper safety mechanism that can guarantee collision-free driving in emergency situations. For example, ACC systems have to be overruled by drivers by performing hard braking to avoid a collision under critical conditions (Wang et al. 2016). Such a critical condition could for example be the platoon approaching a jam tail. Since the leader vehicle of a platoon cannot communicate with its predecessor, its usage of an ACC system might compromise the safety of the entire platoon under such critical conditions.

The conditions in which the (C)ACC controller frameworks discussed can be applied is thus limited. To define the boundaries between which the controllers are applicable, a gap-relative speed diagram (see Figure 2.4) can be used that visualizes this applicable area for a certain vehicle speed of the vehicle in question (Godbole et al. 1999). The gap is defined as the longitudinal distance between two consecutive vehicles. The relative speed is positive if the follower vehicle is travelling slower than the leader vehicle. In the diagram, the straight line between A and B indicates the switching point of the (C)ACC system between cruising mode and car-following mode. In the area above this line, the (C)ACC system is in cruising mode and in the area below the line it is in car-following mode (the marked area). Moreover, there is a line below which the ACC system is not functional and only manual driving is feasible.

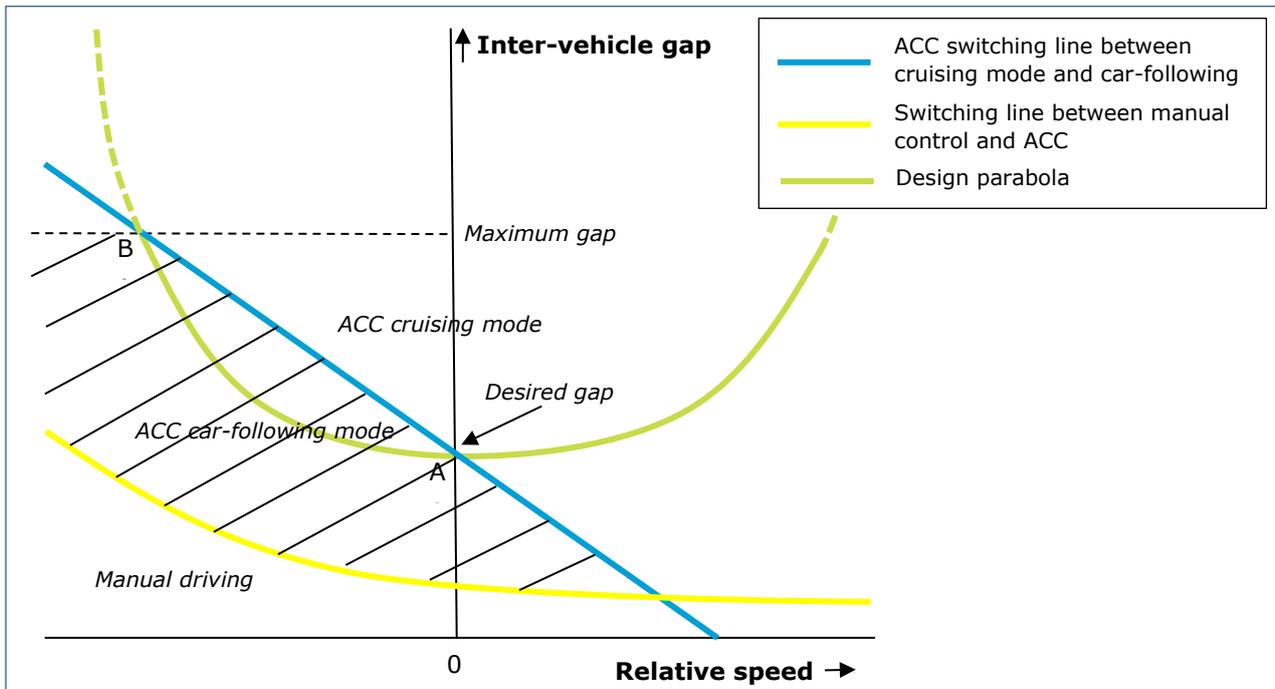


Figure 2.4: Gap-relative speed diagram displaying the applicable area of the proposed (C)ACC controllers (adapted from (Godbole et al. 1999)).

The critical conditions are thus when a vehicle is in car-following mode and driving at a much higher speed than its predecessor. This situation becomes even more critical when at the same time the actual gap is below the desired gap. This implies that when in car-following mode, relative speed and gap thresholds have to be defined that make sure the (C)ACC system either applies some kind of active braking or gives back control to the human driver.

2.1.7 Possible solutions to (C)ACC controller framework limitations

The limitations of the controllers do not imply that the controllers are useless in practice. However, it may limit the number of situations in which they are applicable. To increase the number of situations in which the controllers are applicable, possible solutions to the limitations are explored.

Vehicle capability and comfort constraints

To prevent acceleration and decelerating beyond the vehicle's capabilities, the desired acceleration can be constraint to a maximum and a minimum value, which will therefore be done in this research as described in section D.2.3 of **Appendix D**.

A way to deal with the variability in capabilities of trucks is to add a truck specific 'low-level' controller in addition to the (C)ACC controller. The low-level controller determines the input commands to the engine and the braking system. It uses the input of the (C)ACC controller as well as vehicle-specific parameters (related to acceleration and braking capabilities, e.g. characteristics of the power train, the brakes and the current weight) to determine the actual acceleration/deceleration. In this research, differences in vehicle capabilities are left out of consideration and the low-level controller will be identical for all equipped trucks.

String stability criterion

A string stability criterion can be formulated to obtain the information on minimum gap settings and vehicle characteristics that are necessary to make a platoon string stable. However, apart from the common goal of considering amplification of oscillations upstream a string of vehicles, literature differs in the signals for which the oscillations are considered (Naus et al. 2010). If focussing on preventing collisions, the errors between the desired and actual inter-vehicle gaps are often considered. If focussing on for example traffic jams, absolute vehicle positions or vehicle speeds are considered. Different criteria result depending on whether considering homogeneous or heterogeneous traffic. These result in different criteria for string stability. In this research, an ideal string stability criterion will be used to tune the parameter values of the CACC controller (section 3.3).

As mentioned before, the communication and actuator delay also influence string stability. Depending on the size of the total delay, the stability criterion will thus become more strict than in the ideal situation without any delay. This implies the need of tuning the CACC controller parameters even further to guarantee collision-free driving, which is also addressed in section 3.3.

The communication delay can be implemented as the time step difference, as is done in the algorithms by using the predecessor information from the previous time step. The time step should therefore be similar to the communication delay. Given the findings from earlier research (Nieuwenhuijze et al. 2012) as described in the previous section, the time step will therefore be set at 0.2 s, as is also explained in section 3.1.1. The actuator lag could be implemented by introducing a new variable that represents the actual acceleration. This actual acceleration is calculated from the known acceleration of the previous time step plus its difference with the desired acceleration in that time step multiplied by the ratio of the time step and the actuator delay. However, the actuator delay is usually small compared to the communication delay and the resulting difference in acceleration is thus small (Nieuwenhuijze et al. 2012). An actuator delay will therefore not be applied.

Bi-directional communication

By using a bi-directional communication lay-out in which followers can also transmit information to leaders, the cohesion of platoons can be improved. Platoon leaders can then adjust their driving behaviour so that the platoon remains intact. However, recent research indicates some undesirable side effects of bi-directional communication, such as shockwaves moving upstream and then reverberating after which they move back in downstream direction (Zegers et al. 2017). Since differences in acceleration and braking capabilities between trucks in a platoon are not considered in this study, a bi-directional communication lay-out will not be applied in this study.

Maximum platoon size

A maximum platoon size could be embedded in the law to prevent unacceptable negative effects of truck platooning due to very long platoons. The reasons why the number of vehicles in a vehicle platoon has to be limited should be carefully considered to determine which of the constraints is determining for the maximum platoon size. In the present situation, the largest limitation is expected to arise from what is considered acceptable from a user point of view. However, also very relevant for this study is the need to provide sufficient gaps for vehicles to merge at a motorway on-ramp. Given these considerations, the maximum platoon sizes that will be used in this research are determined in section 4.2.2.

Safety mechanisms

As mentioned in the previous section, two approaches are possible to improve the applicability of the proposed (C)ACC controllers in critical conditions.

Collision avoidance system

The first option is to introduce a collision avoidance system. Such a system that integrates ACC and collision avoidance can be called a full range ACC system. Such a full range ACC (FRACC) system allows the vehicle to drive without driver intervention over the entire speed range.

Several designs for such a system are possible. For example, one can design a system that uses multiple driving modes, differing in the level of safety (Moon et al. 2009). The system then switches between modes depending on the value of a safety indicator, among which the inverse time to

collision (TTC) safety indicator. Each mode could use its own control strategy suitable for the level of safety. In previous studies it was shown that such approaches indeed manage to handle longitudinal control safely (Mullakkal-Babu et al. 2016).

However, such an approach can lead to undesirable acceleration behaviour because switching between the modes is deterministic. This can lead to discontinuous accelerations and high deceleration values in emergency braking situations. Large jerks and abrupt acceleration fluctuations can also occur, especially in situations in which a vehicle cuts in ahead (Mullakkal-Babu et al. 2016). This is illustrated in Figure 2.5, where the response value of the inverse TTC ($1/s$) is largely unresponsive to the value of the distance gap with the predecessor, until it suddenly increases tremendously when the gap becomes very small. The impact of such a controller on traffic flow stability and capacity are not yet understood since their performance in a vehicle platoon has not been tested.

In (Mullakkal-Babu et al. 2016), a FRACC design is proposed to overcome the limitations of other FRACC systems. It integrates ACC and collision avoidance into a single non-linear mathematical formulation. This is achieved by multiplying the relative speed error term in the ACC equation that calculates the desired acceleration by an error response function. This is a sigmoidal function of the distance gap with the predecessor according to **equation (2.15)**.

$$R(s) = \frac{-1}{1 + Qe^{-\left(\frac{s}{P}\right)}} + 1 \quad (2.15)$$

Where:

Q : aggressiveness coefficient (based on maximum value of response, i.e. $R(s=0)$) [-]

P : perception range coefficient (based on detection range of forward looking sensors) [m]

This formulation ensures a strong braking response when approaching the predecessor with a small inter-vehicle gap and a milder braking response when the gap is larger. When using this formulation in the ACC equation, the desired acceleration will smoothly go to zero as the sensor perception range increases. By choosing the right values for Q and P , the controller can be tuned to match the acceleration behaviour of human drivers. This controller enables smooth transition between accelerations and large jerks are also prevented. In the experiments conducted in this study, a aggressiveness coefficient of 1 and a perception coefficient of 100 m are proposed as feasible values. The response of this collision avoidance function to the distance gap has been drawn in Figure 2.5 for two different value sets of Q and P . It can be seen that the response value reacts much more smoothly to the value of the distance gap as compared to the inverse TTC.

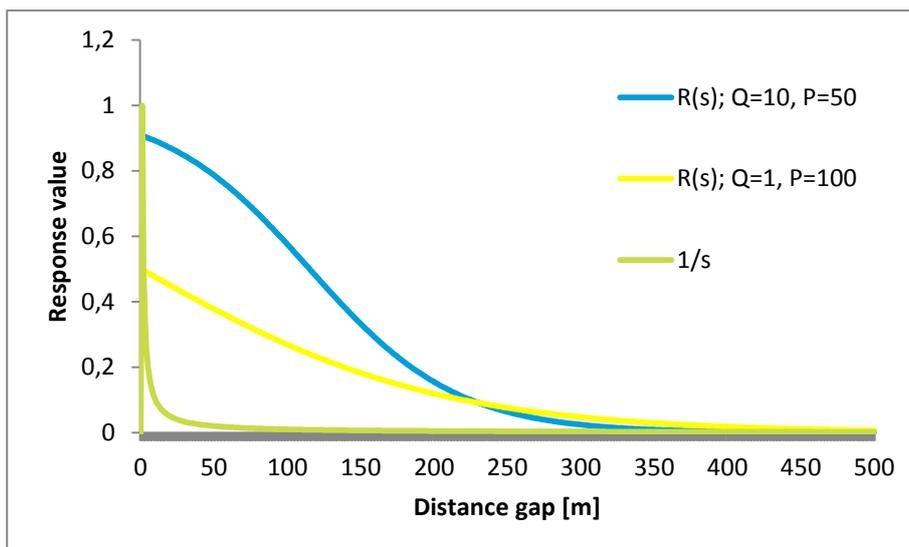


Figure 2.5: Comparison of different response functions for collision avoidance (adapted from (Mullakkal-Babu et al. 2016)).

The introduction of this collision avoidance system in the (C)ACC controller makes a new calibration of the model parameters necessary. In (Mullakkal-Babu et al. 2016) the parameter values of k_s and $k_{\Delta v}$

were found to be 0.18 and 1.93 respectively. These values ensured that the acceleration response will not overshoot and oscillate. However, this was only tested for inter-vehicle gaps of 0.63 s and higher. When using smaller CACC gaps, the values should therefore be recalibrated to meet these stability demands in order to prevent collisions, which will be addressed in section 3.3.

Transition of control to human driver

The second option is to introduce a collision warning system that warns human drivers to retake control. A major disadvantage of such a system is that it suddenly increases a driver's workload and due to a human driver's reaction time this increases the probability of a collision occurring. Especially since the driver is not necessarily paying attention during automated driving, his reaction time can be longer than usual.

In (Xiao et al. 2017) a forward collision warning system is proposed that decides when control should be transitioned to the human driver. Thereby two approaches to trigger a transition of control can be identified. The first possibility is two have a spacing threshold. If the gap with the predecessor is smaller than a safety threshold value, the collision warning system will warn the human driver to take over control. The other approach is based on drivers' perception of critical situations and can for instance use a time-to-collision indicator. A possibility is to use a probability indicator which is the inverse of time-to-collision and vehicle speed as in **equation (2.16)**.

$$TC(s) = \frac{\Delta v}{s} \quad (2.16)$$

Where:

$TC(s)$: transition of control value (function of the distance gap s) [1/s]

Δv : relative speed difference with the predecessor [m/s]

s : distance gap with the predecessor [m]

The value of TC should be calculated every time step to be able to determine when the collision warning system should be activated. From **equation (2.16)** it can be seen that the value of TC will be larger when the time-to-collision is smaller and vice versa. Thus a threshold value of TC can be defined above which the collision warning system is activated and the human driver is urged to take over control. In such a case the model switches from (C)ACC car-following to a car-following model that represents human driving behaviour. This switch takes place with a time delay due to the driver's reaction time. Since the driver is assumed being unprepared to the collision warning he takes longer than usual to get ready to perform the driving task. Therefore a time delay of 1 s between the first warning and actual braking can be assumed (Xiao et al. 2017).

A decision on whether to implement the collision avoidance system or transition of control in the (C)ACC controller that will be applied in the simulations is made in section 3.4.1 where the performance of both types of safety mechanisms is verified for several typical driving scenarios.

2.1.8 Conclusions on modelling longitudinal truck platoon driving behaviour

There are several (C)ACC controllers that can be used to control the longitudinal driving behaviour of truck platoons. A controller using a CTG strategy gives the most plausible driving behaviour with respect to string stability and safety and is the most practical, acceptable and common application of CACC as well as with what is most likely applied by OEMs (Ioannou and Chien 1993, Naus et al. 2010). Therefore, a controller with CTG strategy is chosen to be implemented in a simulation model. For communication with platoon members, multiple plausible options exist. A multi-anticipative controller is most common and generates the most plausible driving behaviour. The differences in performance of multi-anticipative controllers with single and multiple predecessor anticipation needs to be verified in order to determine which one generates the most plausible driving behaviour. A standstill distance is included to prevent collisions at standstill. Moreover, acceleration restrictions are added to the controller to match the vehicles' capabilities. To overcome the insufficient performance of the controllers in critical conditions, a collision avoidance strategy will be used and the controller parameters will be tuned to guarantee collision-free driving. The differences in performance of a controller with the proposed collision avoidance system and a controller with transition of control to the human driver are therefore also verified.

2.2 Simulation of human driving behaviour

In the simulation of driving behaviour, we distinguish two components. On the one hand there are the traffic behaviour models, i.e. algorithms that together try to describe driving behaviour. These usually consist of car-following models and lane change models that describe the longitudinal and lateral driving behaviour respectively. On the other hand there are the simulation platforms, or software tools, in which these models are or can be implemented.

To get insight into how human driving behaviour is modelled, existing driving behaviour models will be studied first in this section. In that way their suitability for modelling merging behaviour in mixed automated and non-automated traffic in simulation becomes clear. Also, the limitations of these models are explored so that possible effects of these limitations on simulation results can be taken into account. This is especially important since according to (Broekman 2017), current models have difficulty simulating traffic behaviour around motorway ramps. An exploration of the models' most important characteristics and their strengths and weaknesses is performed. Some of the models have been implemented in traffic simulation tools. These applications in simulation tools are also listed so that the practical availability of the models can also be taken into account in the model choice.

Longitudinal driving behaviour models are first discussed in section 2.2.1, after which lateral driving behaviour and corresponding models are elaborated on in section 2.2.2. A short overview of integrated models, in which both the longitudinal and the lateral driving behaviour is integrated in one modelling framework is given in **Appendix B**. An exploration of existing simulation platforms and their integrated driving behaviour models is performed in section 2.2.3. A more detailed description of the platforms is given in **Appendix C**. By comparing their abilities to model the desired behaviour and their strengths and weaknesses, a decision is made on which simulation platform to use for this research. Conclusions on the simulation of human driving behaviour are drawn in section 2.2.4.

2.2.1 Longitudinal behaviour models

Within longitudinal driving behaviour models, two main driving regimes are usually considered: free flow regime and car-following regime. A vehicle driving at its desired speed is in the free flow regime. If a vehicle cannot drive at its desired speed because there is a vehicle in front of it, it is in the car-following regime. The vehicle's speed and acceleration are adapted to that of its predecessor. Car-following models can be classified into eight main groups: stimulus-response models, collision-avoidance models, linear models, psycho-physical models, optimum velocity models, fuzzy logic models, cellular automata models and prospect theory models. A summarizing overview of the most important features of the car-following models including their strengths and weaknesses is given in Table 2.3. Their uses in the simulation platforms of section 2.2.3 are also given. A more elaborate description of the models can be found in **Appendix B**.

It can be concluded that there is an enormous number of longitudinal human driving behaviour models, especially car-following models. Considering the strengths and weaknesses of the models, it seems that especially collision-avoidance and psycho-physical models are suitable to apply in simulation. From the collision-avoidance models especially the IDM+ (Schakel et al. 2012) and from the psycho-physical models especially the Wiedemann (Olstam and Tapani 2004) model are promising to apply in simulation. These models are already implemented in the simulation tools MOTUS and VISSIM respectively (see Table 2.3 and **Appendix C**). Other models seem to be more limited in their ability to model longitudinal driving behaviour or there is simply too little information on how to apply them.

Table 2.3: Overview of the most important characteristics of car-following models.

Model type	Example model	Implemented in simulation tool	Basic decision variables	Driver reaction time	Control parameters	Heterogeneity	Advantages	Disadvantages
Stimulus-response	GM ¹ , GHR ¹ , Ahmed ¹	MITSIMLab ²	Relative speed	Yes	Yes	In enhancements	Multiple enhancements	No thresholds
Collision-avoidance	Gipps ¹ IDM ¹ IDM+ ¹ Zhang et al. ¹	AIMSUN ² MATLAB ² MOTUS ² , OTS ² CORSIM ²	Safe distance	Yes (some)	Yes	In enhancements	Multiple enhancements	Safe distance not always realistic
Linear	Helly ¹	-	Rel. speed, gap, desired gap	Yes	Yes	No	Good fit to observed data	Mainly for low speed urban networks
Psycho-physical	Wiedemann ¹	VISSIM ²	Rel. speed, gap	Possible	Possible	Yes	Multiple regimes, thresholds	-
Optimal velocity	OVM ¹ , FVD ¹ , AFVD ¹	-	Deviation from desired speed, gap	No	Yes	No	Simple	Not very realistic
Fuzzy logic¹	-	-	Unknown	Unknown	Unknown	Yes	Simple	Hardly used
Cellular automation¹	-	-	Unknown	Unknown	Unknown	Yes	Computationally efficient	No proper coordinates estimation
Prospect theory¹	-	-	Effects of choices based on human perception and judgement	Unknown	Yes	Yes	Incorporates effects of choices	Subjective

¹ See **Appendix B**.² See section 2.2.3.

2.2.2 Lateral behaviour models

Lateral behaviour models describe lateral vehicle movement, also called lane change behaviour. A lane change is defined as the movement of a vehicle on a road with multiple lanes from one lane to an adjacent lane. Lane change behaviour has not been studied as extensively as car-following behaviour. However, because of increased computational capability, computers can deal with more complex models as well as process more empirical data on lane change behaviour. This has increased the ability to define more complex lane change models (de Azevedo 2014). Current lane change models can be categorized in four different groups: rule-based models, discrete choice models, incentive-based models and artificial intelligence (AI) models. A summarizing overview of the most important features of the models including their strengths and weaknesses is given in Table 2.4. Their uses in the simulation platforms of section 2.2.3 are also given. A more elaborate description of the models can be found in **Appendix B**. First, however, some general information on lane change models in general is given to better understand how these models are structured and how well they perform.

Lane change types

Two lane change types are most commonly distinguished by models: discretionary and mandatory lane changes (Kesting et al. 2006, Kolen 2013). Discretionary lane changes are performed to improve the driving conditions for the driver or to improve the driving conditions for other drivers. An example of the former is to overtake a slower vehicle and an example for the latter is to give room to vehicles driving on an on-ramp or to vehicles passing a slower vehicle. Mandatory lane changes are performed to keep following the correct route. An example is changing lanes towards an exit or to the right in case of a lane drop or moving from an on-ramp to the main road.

Other classifications also exist. For instance (Hidas 2002, Hidas 2005) distinguishes free, forced and cooperative lane changes. (Schakel et al. 2012) classifies lane changes by the way they are prepared and performed. Thereby lane change processes are defined and depending on the level of desire of drivers, a certain lane change process is performed.

Model structure

All theories and models describing lane change behaviour at a microscopic level are based on gap acceptance. They differ, among other things, in the way the critical (acceptable) gap is derived and which other behavioural aspects are used.

Most of the time a lane change model consists of three components: a decision model, a condition model and a manoeuvre model. The decision model considers decision variables for taking the decision to perform a lane change. The decision variables include the route plans, the current lane type and the driving conditions in the current and adjacent lanes. The condition model describes acceptable conditions for different types of lane changes. The manoeuvre model describes the vehicle's speed and the duration of the lane change (Daamen et al. 2010).

(Kesting et al. 2006) also defines a comparable structure with three steps in modelling lane changes: the strategic stage (route determination in the network), the tactical stage (preparation and initiation of an intended lane change by advance acceleration or deceleration) and the operational stage (assessment of safety and desirability of the lane change). Yet another, more hierarchical way to describe the lane change process is by dividing it in different steps: (1) consider a lane change, (2) choose a lane, (3) search for an acceptable gap and (4) select a trajectory for the lane change. Again this structure is comparable to the previous two (de Azevedo 2014).

Performance of the existing lane change models

According to (Daamen et al. 2010), the degree to which microscopic simulation modelling to represent lane change behaviour is realistic was then questionable. The focus of research has mainly been on longitudinal driver behaviour, especially car-following behaviour. Lateral driving behaviour such as lane change behaviour has been researched less. Nevertheless a fair amount of research has been performed on lane change behaviour and merging behaviour more specifically. However, according to (Daamen et al. 2010), at least up to 2010, there was no model that combined a proper decision structure with the incorporation of the effects of lane changes on traffic flow. It was found that the effect of lane changes on traffic conditions is not negligible and that lane changes can cause a capacity drop, but most models are unable to capture these effects.

Also according to (Daamen et al. 2010), the main factors influencing motorway merging behaviour are the merge location and its relation to prevailing driving conditions, gap acceptance and the relaxation phenomenon. Courtesy yielding and cooperative lane changing seem to have a significant effect on lane change behaviour as well, but only (Wang 2005) incorporate these in their model. (Smith 1985) incorporated relaxation, which is likely to also have a significant effect on traffic flow. The relatively new LMRS (Schakel et al. 2012) seems to be able to take away some of these shortcomings by introducing a new decision structure combined with relaxation and synchronization.

LMRS: Lane-change Model with Relaxation and Synchronization

One of the most recent models is the **Lane-Change Model with Relaxation and Synchronization (LMRS)** (Schakel et al. 2012). It is an incentive-based model, meaning that lane changing is decided on by desire. This desire is determined by a combination of route following, speed gaining and 'keep right' incentives. Lane changes are classified based on the way in which they are prepared and performed, i.e. based on behaviour depending on the level of lane change desire. As desire increases, drivers become more assertive to change lanes. The model distinguishes free lane changes, synchronized lane changes and cooperative lane changes. The model achieves some integration with car-following behaviour by including behaviour for relaxation and synchronization, as the name of the model suggests.

Relaxation is the phenomenon of slowly decelerating upon completing a lane change in order to increase the gap to the desired gap. Synchronization is the phenomenon that a vehicle adapts its speed to the speed of the vehicles in the target lane when about to execute a lane change manoeuvre.

In addition to synchronization, differences in accepted gap and deceleration are applied depending on driver's lane change desire. For higher desire, drivers are willing to accept smaller gaps and decelerate more. The maximum deceleration is smaller than in most existing lane change models. This is achieved by allowing for relaxation and synchronization.

According to (Schakel et al. 2012) in the real world, drivers often will apply these small decelerations when merging and will accept relatively small time gaps for a while (relaxation), as is shown by empirical research. Drivers will also prepare their lane change, adapting their speed to align with a gap and in which another driver may create a gap by changing his speed (synchronization). The inclusion of cooperative lane changes in the proposed model is defensible as empirical evidence exists that drivers are willing to create a gap at an on-ramp, since no merging vehicle is overtaken by multiple vehicles (Daamen et al. 2010).

The developers of the LMRS recognized the need to develop a new lane change model that shows better resemblance with the real world. The main points of attention thereby are the amount of traffic on each lane (lane distribution), and the speed driven on each lane (lane speed). They intended to make the model applicable for various road layouts and various levels of traffic density. Therefore multiple lane change incentives were included in the model. A secondary important requirement was that the model would be able to model traffic dynamics well. These include the onset and progression of congestion. This was achieved by including relaxation and synchronization. A final requirement was that it should be possible to calibrate the model. This means that the number and complexity of parameters should be limited.

Given these ambitions of the developers, the LMRS is able to better model the amount of traffic volume per lane, the traffic speeds in different lanes and the onset of congestion. By including relaxation and synchronization some integration with a car-following model is achieved. Another improvement of the model is the inclusion of trade-offs between lane change incentives (e.g. between mandatory and discretionary lane changes). The use of anticipation speed for the speed gain incentive is also an improvement compared to earlier models. Disadvantages of the model also exist. After calibration, it was found that sometimes the model had some difficulties modelling congestion well. The fit in congestion is not very clear because it depends highly on the stochastic input.

The LMRS has only seven parameters, making it relatively easy to calibrate. Loop detector data were used to calibrate and validate the model. It is already implemented in the simulation software tool MOTUS and will be implemented in OTS (see section 2.2.3). LMRS can be used with any car-following model that calculates vehicle acceleration.

Conclusion on lateral behaviour models

Considering the practical usability of lateral human driving behaviour models in simulation, especially rule-based (Gipps type) and incentive-based models seem suitable for use in simulation. Discrete choice models may also be suitable but are more complex to implement. Considering the degree to which the models are able to represent realistic lane change behaviour, many models do not perform well with respect to the decision structure determining the acceptable gap as well as the failure to incorporate the relaxation phenomenon. Courtesy yielding and cooperative lane changing seem to have a significant effect on lane change behaviour as well, but only few models address these phenomena. The LMRS seems to be able to take away some of these limitations by achieving some integration with car-following by including synchronization and relaxation. By including trade-offs between lane change incentives a better decision structure was realized as well. Moreover, it is relatively easy to calibrate because of the limited number of parameters. These advantages make it a promising model to use in simulation.

2.2.3 Simulation platforms

The most well-known and most commonly used simulation platforms that are available are researched to determine their suitability of simulating truck platooning in mixed traffic and on-ramp merging behaviour. A summarizing overview of the advantages and disadvantages of each is given in Table 2.5. A more detailed description of the platforms is given in **Appendix C**. Subsequently, the performances of the platforms are compared on several criteria, after which the scores on the criteria are determined in Table 2.6 so that a choice of platform can be made.

Table 2.4: Overview of the most important characteristics of lane change models.

Model type	Example model	Use in simulation tool	Basic decision structure	Basic decision variables	Lane change types	Control parameters	Heterogeneity	+	-
Rule-based (Gipps-type)	Halati et al. ¹ Barceló and Casas ¹	CORSIM ² AIMSUN ² VISSIM ² FOSIM ²	Decision tree: (1) Possibility (2) Necessity (3) Desirability	(rel.) speed, gap	Mandatory, discretionary (Gipps), forced, cooperative (in enhancements)	Yes	Only in enhancements of Gipps	Clear structure allows straight-forward algorithms	Primarily meant for urban networks
Rule-based (game theory ¹)	-	-	Pay-off matrix per player (vehicle)	Any	None	Unknown	Yes	Endless possibilities to determine behaviour	No practical research examples
Rule-based (cellular automation ¹)	-	-	Grid-based space system per driver category	Any	None	Unknown	Yes	Computationally efficient for large-scale networks	No proper coordinates estimation framework
Discrete choice	Choudhury and Toledo ¹	MITSIMLab ²	Choice probability based on lane change utilities (e.g. logit)	Critical gap	Mandatory, discretionary	Yes	Yes	Realistically mimics human choice behaviour	More complex decision structure
Incentive- based (MOBIL)	MOBIL ¹	MATLAB ²	Trade-off between attractiveness and risk	Possible acceleration based on safety, (rel.) speed, keep right	Mandatory, discretionary	Yes	Yes	Politeness factor per lane change type, acceleration threshold value	No integration with car-following
Incentive- based (LMRS)	LMRS	MOTUS ² , OTS ²	Level of assertiveness depending on desire	Route, speed, keep right	Free, synchronized, cooperative (determined by level of assertiveness)	Yes	Yes	Some integration with car-following by including relaxation and synchronization	Sometimes has difficulties modelling congestion
Artificial Intelligence¹	-	-	Numerous (ANN)/if-then rules (fuzzy logic)	Any	None	Unknown	Yes	Can have good fit to empirical data (ANN)	Black box (ANN)/extremely complex (fuzzy logic)

¹ See **Appendix B**.² See section 2.2.3.

Table 2.5: Advantages and disadvantages of the different traffic simulation software platforms.

Platform / characteristics	Advantages	Disadvantages	Special characteristics
VISSIM¹	<ul style="list-style-type: none"> Easily available Huge flexibility Unlimited number of vehicle classes can be defined External driver behaviour can be implemented using DLL plug-in 	<ul style="list-style-type: none"> Hard to calibrate due to large number of parameters Overestimates the number of discretionary lane changes The workings of many functions remain unclear 	<ul style="list-style-type: none"> Vehicles can display different behaviour at different locations Thresholds prevent reaction to minor changes
MOTUS¹	<ul style="list-style-type: none"> No black boxes, full understanding of inner workings possible Relatively simple programming in Java allows adaptation and extension of the model Allows focusing on specific parts of complex networks during simulation Relatively realistic car-following and lane change models (with relaxation and synchronization) Support available at the TU Delft 	<ul style="list-style-type: none"> Limited graphical user interface No manuals available Limited functionality Especially car-following model still has some drawbacks (no driver reaction time, no thresholds to prevent reaction to minor changes) 	<ul style="list-style-type: none"> Incorporates OBUs and RSUs that can interact. Open source
OTS¹	<ul style="list-style-type: none"> Similar to MOTUS, but more complex programming and increased functionality for more accurate results 	<ul style="list-style-type: none"> Similar to MOTUS, but more programming skills required and increased functionality Parts still under construction 	<ul style="list-style-type: none"> Open source
AIMSUN¹	<ul style="list-style-type: none"> No overtaking on on-ramp Driver heterogeneity in terms of aggressiveness 	<ul style="list-style-type: none"> Somewhat of a 'black box' 	<ul style="list-style-type: none"> Both microscopic and mesoscopic modelling Vehicles can display different behaviour in three different behavioural zones
CORSIM¹	<ul style="list-style-type: none"> Prevents ping-pong effects of lane changes Desired speed at on-ramp based on adjacent lane speed for smooth merging 	<ul style="list-style-type: none"> May miss European traffic rules e.g. 'keep right'. Limited number of driver classes limits heterogeneous behaviour 	<ul style="list-style-type: none"> Incorporates extra type of lane change: random lane change 3 second threshold for lane changes
FOSim¹	<ul style="list-style-type: none"> Calibrated for the Netherlands Designed for motorway corridors Straightforward user interface Extensive manual and even a basic course available 	<ul style="list-style-type: none"> Old core may miss recent insights into lane change behaviour No heterogeneous driving behaviour Many parameters are fixed or can hardly be changed Limited number of driver classes Location of merging doubtful Little interaction between lanes 	<ul style="list-style-type: none"> Vehicles at an on-ramp can always merge if allowed deceleration is set high enough
MITSIMLab¹	<ul style="list-style-type: none"> Open source nature allows full understanding Extensive GUI 	<ul style="list-style-type: none"> Meant mainly to evaluate the effects of traffic control measures Runs on Linux OS Transition of acceleration behaviour between free flow and car-following not smooth No cooperative lane changing 	<ul style="list-style-type: none"> Open source Can implement traffic control measures
MATLAB applications¹	<ul style="list-style-type: none"> Relatively easy programming Can easily interact with other programs Obtain any performance indicator 	<ul style="list-style-type: none"> Limited functionality of existing simulation codes No driver reaction time, no thresholds to prevent reaction to minor changes 	<ul style="list-style-type: none"> Interaction with other programs Politeness factor per lane change type, acceleration threshold value

¹ See Appendix C.

Performance criteria

To decide whether a simulation platform models the desired situation sufficiently realistic, the next performance criteria are applied. The platform with the best overall score is chosen for this research.

- The model simulates at the microscopic level (i.e. models the behaviour of individual vehicles separately) so that individual vehicle behaviour can be monitored.
- The incorporated car-following model is well able to model motorway car-following behaviour of human drivers:
 - A human reaction time delay is preferably included.
 - Thresholds ensure that drivers do not react to every minor change in driving conditions.
 - Car-following behaviour is heterogeneous by including stochasticity. For example include variable thresholds, desired speeds, desired acceleration/deceleration and reaction times.
 - Smooth transition between free flow and car-following regimes.
 - Control parameters allow for calibration.
- The incorporated lane change model is well able to model motorway on-ramp merging behaviour of human drivers:
 - The decision structure represents human decision making.
 - Lane change behaviour is heterogeneous by replicating the stochastic process of human decisions. For example include a variable desired speed.
 - No unrealistically large decelerations of vehicles on the motorway when a vehicle merges in a very small gap. Thus some form of cooperative behaviour is included, e.g. courtesy yielding or relaxation.
 - A 'keep right' incentive is included to be able to represent the situation on Dutch motorways.
 - Control parameters allow for calibration.
- The model is adaptable to include vehicles with cooperative adaptive cruise control functionality to model longitudinal truck platoon driving behaviour.
- The model can generate the desired output, i.e. the relevant performance indicators that allow quantification of traffic performance and safety effects. An overview of the performance indicators that will be used is given in section 4.3 of Chapter 4.
- The model can register if a vehicle is unable to merge to be able to capture truck platooning effects on the ability to merge.

In addition to these performance criteria, there are several practical criteria that should be satisfied:

- The simulation model has to be available for use for this research.
- The complexity of setting up the simulation environment and possible programming has to be limited because of limited programming skills and time constraints.
- Technical support should be available to guard the quality of the simulations and for help with (programming) problems.

Scores

Given these performance and practical criteria, the scores of the platforms and their models can be found in Table 2.6.

Table 2.6: Scores of the traffic simulation software platforms on the criteria.

Criterion/Platform	VISSIM	MOTUS	OTS	AIMSUN	CORSIM	FOSim	MITSIMLab	MATLAB applications
Microscopic	✓	✓	✓	✓	✓	✓	✓	✓
Car-following								
Reaction time	✗	✗	✗	✓	?	?	✓	✗
Thresholds	✓	✗	✗	✗	✓	✓	?	✓
Heterogeneity	✓	✓	✓	✓	0	✗	✓	✓
Regime transition	✓	✓	✓	?	?	✓	✗	✓
Control parameters	✓	✓	✓	✓	✓	✓	✓	✓
Lane changing								
Decision structure	+	++	++	+	+	+	+	+
Heterogeneity	+	+	+	+	0	✗	+	✓
Cooperativeness	+	++	++	✗	0	✗	✗	✗
Keep right	✓	✓	✓	✓	✗	✓	✓	✓
Control parameters	✓	✓	✓	✓	✓	✓	✓	✓
Adaptable for CACC	✓	✓	✓	?	?	Limited	?	✓
Desired output	✓	✓	✓	✓	✓	✓	✓	✓
Merging ability	✓	✓	✓	?	?	✗	?	✓
Availability	✓	✓	Under construction	?	?	✓	?	✓
Complexity	High	Medium	High	?	?	Low	?	Low
Support	✓	✓	✓	✗	✗	✓	✗	✓

2.2.4 Conclusions on simulation of human driving behaviour

When modelling the situation of human drivers merging at a motorway on-ramp, it is crucial that the models used in simulation sufficiently approach reality in merging situations. If the merging behaviour is not realistic, neither will the traffic performance and safety effects of the merging behaviour be realistic. This would undermine the validity of the entire study. Therefore the simulation software platform chosen should incorporate (or be easily adaptable to incorporate) realistic merging behaviour. This means that the displayed lane change behaviour should have a realistic influence on traffic conditions. In that way the effects of this merging behaviour on traffic flow and traffic safety can be measured.

This means that not every model is suitable for this research. The lane change model used is of great importance as is the interaction with car-following behaviour to display cooperative behaviour. The decision of the merging vehicles when to merge is also crucial for realistic behaviour, indicating the importance of the merging decision structure. To account for more realistic lane change decisions, variability among drivers is also of big importance. Finally, technical support must be available as a guarantee for the quality of the simulations.

Summarizing the scores on the performance criteria and practical criteria of all tools explored, it is therefore concluded that MOTUS is the most promising tool to use and will therefore be used.

2.3 Behavioural adaptation in the presence of truck platoons

It is important to know how human driving behaviour changes in the presence of truck platoons so that this adapted behaviour can be captured in simulation, improving the validity of the modelling. Since truck platooning is not applied in practice yet, there is little evidence on what these adaptations might be. There is however some information available on situations that are to a certain degree comparable to truck platooning. One of these information sources is the EU truck platooning challenge (Eckhardt 2016). Moreover, some platooning effects can be observed from observations from a busy motorway freight route. Another situation is the recent deployment of longer and heavier vehicles (extra-long trucks) on the motorway.

2.3.1 Findings from the EU Truck Platooning Challenge

According to the truck drivers that participated in the EU truck platooning challenge (Maan et al. 2016), human drivers did not react to truck platoons very differently than normally. However, the platoons were sometimes hindered by drivers merging in the platoon at on- and off-ramps. Other situations in which human drivers merged in the platoon did not occur.

Moreover, when human truck drivers entered or exited the motorway and noticed the platoon, they sometimes signalled to the platoon drivers to give them room for merging. Overtaking of the platoons by other truck drivers was sometimes necessary since the platoons were driving at 80 km/h.

Only few problems with the road design were perceived by the participating truck drivers. Places where they were perceived were mainly at on- and off-ramps. These were often perceived as too short, indicating that it was noticed that drivers sometimes had difficulty to merge.

The observations at ramps are of limited value since the platoon decoupled in all situations where other traffic entered or exited the motorway at on- and off-ramps. The platoons also sometimes decoupled in heavy traffic conditions.

2.3.2 Findings from busy motorway freight route

Platoon formation of trucks (non-automated) on the motorway can occur when there is a lot of freight traffic. Especially when there is an overtaking prohibition for trucks this can result in the formation of long platoons: many trucks driving closely together in the right lane. Such an overtaking prohibition is mainly applied on two-lane motorways in the Netherlands. It may lead to merging problems at busy on-ramps (Beenker and Reintjes 2012).

From empirical research on (non-automated) truck platoon formation on the Dutch A15 motorway in 2014 (Jongenotter 2014) several behavioural adaptations and their effects on traffic performance and safety are obtained. A research by (Mansvelter et al. 2014) also supports some of the findings.

Smaller gaps

The share of vehicles maintaining relatively small gaps increases as the number of trucks in a (non-automated) platoon driving on the same lane increases. This is a result of heavy traffic on the lane in question. The reduced gaps cause a reduced perception of the road and traffic conditions ahead. This increases the chance of head-tail collisions. In absence of inter-vehicle communication in the platoon, a small disturbance will lead to congestion faster as instability is increased. This could have a negative effect on travel time reliability.

The reduced gaps also lead to a higher traffic density and could in theory lead to a road capacity increase. However, due to premature lane changing by other vehicles to overtake the platoon, the gap between platoons increases, which has a negative effect on road capacity. The total effects on road capacity in this situation is therefore uncertain.

Risky lane change behaviour

Possibly drivers also take more risks when changing lanes, accepting smaller gaps. Especially in heavy traffic this can cause shock waves. As vehicles in the right lane cannot accelerate before changing lanes, they cannot adapt to the speed in the left lane. This causes shockwave effects in the left lane with an increased chance of head-tail collisions

Lane distribution

At high traffic intensities and many trucks, an increased number of vehicles will overtake the (non-automated) truck platoons. This leads to the creation of (non-truck) platoons in the left lane. It will also lead to premature lane changing to the left and delayed lane changing to the right. Because of this, at higher traffic intensities the left lane will be used more than the right lane. As the right lane will be used less, this might have a negative effect on road capacity. As more vehicles will overtake, the share of traffic driving below the speed limit in the left lane will increase. The result is that the traffic flow becomes more turbulent, i.e. more speed variations occur. Also, the chance that vehicles in the (non-automated, non-truck) platoon in the left lane are overtaken on the right increases, resulting in less predictable situations and hence decreasing traffic safety. As a relatively slow vehicle overtakes a platoon, an increasingly large gap in front of it will form. The size of this gap will increase as the platoon is longer.

Merging behaviour

The effect of platooning on merging behaviour at on-ramps have not been quantified, but the following possible driving behaviour and their possible effects are distinguished:

- **Merge too early**
If drivers upon entering the acceleration lane immediately perceive that there are probably only little sufficient gaps, they can choose to merge right at the beginning of the acceleration lane. This will often lead to merging with relatively low speed, hindering the traffic upstream by causing disturbances. This can lead to increased speed variations and ultimately head-tail collisions.
- **Brake to be able to merge**
Drivers can also brake and merge behind the platoon. This is most likely when the end of the acceleration lane is near. Again this will lead to merging with a relatively low speed. In the extreme case drivers can come to a standstill at the end of the acceleration lane. This can lead to severe collisions with oncoming traffic.
- **Accelerate to be able to merge**
If drivers perceive that the only (or closest) suitable gap is in front of the platoon, they could choose to accelerate to be able to merge in front of the platoon. Given the limited length of the acceleration lane, this is only possible if the platoon is not too long. This merging strategy is likely to have the least effects on traffic performance.
- **Merge too late**
Instead of stopping if an acceptable gap does not occur, drivers could choose to continue driving on the shoulder lane. This provides additional time to merge. Drivers on the right lane might be more willing to yield for the merging vehicle or perform a courtesy lane change, which might cause congestion. It is assumed that this will only happen if the merging vehicle meets a platoon of four vehicles or more. Chances thereupon are considered very limited.
- **Stop on the acceleration lane (or the shoulder lane)**

Drivers could decide to stop on the acceleration lane (or the shoulder lane). Again this will lead to merging with a relatively low speed and collisions with oncoming traffic.

- **Merge in the platoon**
A driver could also decide to accept a very small gap and merge within the platoon. The reduced gaps will lead to an increased chance of congestion and head-tail collisions as shockwave effects occur due to the fact that the truck behind the merging vehicle will have to brake.
- **Courtesy yield for the merging vehicle**
A driver in the right lane could also yield for the merging vehicle out of courtesy (courtesy yielding, see also section 2.2.2). Again a shockwave will occur behind the merging vehicle that might lead to congestion and head-tail collisions.
- **Perform courtesy lane change**
A driver in the right lane could also decide to change lanes to the left to create room for the merging vehicle. In that case the shockwave effects could occur in the left lane. It is however unlikely that a vehicle will do this if the left lane is already very full. Moreover, this is not possible at sections where it is prohibited for trucks to overtake.
- **Change to left lane too early after merging**
A merging vehicle might change lanes to the left directly after merging. The merging vehicle can then overtake the platoon immediately. Similar effects as with the courtesy lane change might occur.

In addition to these findings of possible merging behaviour, a quantitative analysis of merging behaviour was conducted by (de Waard et al. 2008). Among other factors it quantifies the difference in average speed and its standard deviation on the acceleration lane, the average merge location and the minimum time gap and time to collision (TTC) after merging, between a situation with mixed traffic and a situation with (non-automated) truck platoons in the right lane of the motorway. The length of the acceleration lane is 300 m.

It is concluded that the speed of merging vehicles on the acceleration lane slightly decreases as the share of trucks in the right lane increases. At the same time the spread in speed on the acceleration lane increases. In general, vehicles tend to merge later when there is a truck next to the merging vehicle. With many trucks in the right lane, merging takes place either behind or in front of the truck that is next to the merging vehicle at the begin of the acceleration lane with the same frequency. Safety margins are smaller when there are a lot of trucks in the right lane: the average minimum time gap and TTC are more than twice as small compared to the mixed traffic situation.

Another simulator study by (Gouy et al. 2014) further supports some of these findings. They found that truck platooning has an effect on the gaps maintained by other drivers. It was found that vehicles passing a platoon maintain significantly smaller gaps when the platoon maintains gaps of 0.3 s. This can have a detrimental effect on safety for the passing drivers.

2.3.3 Findings from the deployment of longer and heavier vehicles

Longer and heavier vehicles (LHVs) are trucks that are extra long and extra heavy. Their maximum length is 25.25 m (compared to 18.75 m for normal articulated trucks). Their use can save fuel. Tests with LHVs have been conducted in the Netherlands since 2000 with the goal to evaluate their safety. Since 2013 LHVs are allowed on dedicated motorway routes. Similar to LHVs, truck platoons can also be regarded as extra long trucks, especially when the gap maintained is so small that vehicles will not merge within the platoon. Therefore some similar effects might occur with the introduction of truck platooning and hence a look is taken at the effects found for LHVs.

In (Hoogvelt et al. 1996, TNS-NIPO Consult 2005, Dijkers and Huijgen 2009) it was found that the subjective safety experience of drivers when interacting with LHVs does not significantly change compared to the case of interacting with normal trucks. The largest safety experience effect was found for the length of the vehicle. Major efforts to raise the public acceptance are regarded unnecessary. However, these results were obtained from a survey and thus contain stated preferences. The revealed preference might be different.

Merging at an on-ramp when there is an LHV in the right lane was found to be the most dangerous traffic situation caused by the introduction of LHVs. It was found that drivers sometimes underestimate the length of an LHV when merging at an on-ramp, so that they have to accelerate to be able to merge in front of the LHV. It is observed that drivers often want to merge in front of the

LHV no matter how dangerous that is, even more often than with a normal truck, although the difference is small. Moreover, underestimation of the length also results in misjudging of the time it takes to perform an overtaking manoeuvre. Although the length thus plays a major role in the safety effects of LHVs, analysis of accidents in (ARCADIS Nederland BV 2015) did not reveal any relation between the length of LHVs and the occurrence of these accidents.

2.3.4 Conclusions on behavioural adaptation

It is expected that drivers will show behavioural adaptation in the presence of truck platoons. At on-ramps, the flow on the acceleration lane will be more turbulent. Moreover, merging vehicles at an on-ramp will, on average, drive slightly slower on the acceleration lane. The average merge location will be located more towards the end of the acceleration lane. Traffic safety might decrease as the gaps accepted by merging vehicles are significantly smaller.

2.4 Conclusions

For the modelling of longitudinal automated driving of truck platoons, a multi-anticipative (C)ACC controller using a constant time gap strategy will be used. It generates the most plausible driving behaviour with respect to string stability and safety and is in line with the most practical, acceptable and common application of CACC as well as with what is most likely applied by OEMs (Ioannou and Chien 1993, Naus et al. 2010). Cruise control will be used if there is no predecessor or if the predecessor is out of the sensor range. Verifying the performance of the controller in simulations of multiple typical driving scenarios representing common traffic situations will determine whether the controller will only communicate with the immediate predecessor or with multiple predecessors as well as whether the controllers will incorporate the collision avoidance system or will return control to the human driver. Thereby the control parameters are tuned to guarantee collision-free driving.

Researching the simulation of human driving behaviour has given multiple insights into the possibilities and limitations of using simulation platforms to simulate truck platooning in mixed traffic at motorway on-ramps. The extent to which the incorporated driving behaviour models are able to generate realistic merging behaviour is crucial for the validity of the simulation results. This means that especially the lane change model and the interaction with car-following behaviour, i.e. the presence of cooperative behaviour is important. The decision structure for when vehicles merge is also of great importance. The IDM+ car-following model and especially the LMRS lane change model and the interaction between these two in MOTUS meet the requirements best. Given these insights as well as the fact that MOTUS meets the simulation tool requirements best, MOTUS is chosen as the simulation tool to use for evaluating the effects of truck platooning in mixed traffic at motorway on-ramps.

Finally, behavioural adaptation of human drivers in the presence of truck platoons implies the need to implement these behavioural changes in the simulation model in order to improve the validity of the simulations. Current research fails to give a complete overview of what behavioural changes can be expected. The most important behavioural adaptation is the acceptance of smaller gaps when merging. This behavioural adaptation will be implemented in MOTUS to make the merging behaviour more realistic.

3 Modelling truck platooning in simulation

The literature study of Chapter 2 has shown how truck platooning can be modelled and what effects truck platooning may have on human driving behaviour. The suitability of human driving behaviour models and simulation platforms were also addressed to determine which models and which platform will be used to simulate truck platooning in mixed traffic. The next steps are to implement truck platooning functionality in the simulation platform of choice, MOTUS, to determine and verify the control parameters of the proposed (C)ACC controller and to validate the adapted simulation model.

Therefore, a specification of the proposed automated driving model that was implemented in MOTUS is first given in section 3.1. An explanation of how this implementation was achieved and the design choices that were made are given in section 3.2. The implemented behavioural adaptations of human drivers are also addressed in that section. The choice of parameter values of the proposed (C)ACC controller is justified in section 3.3 after which the performance of the adapted simulation model with truck platooning functionality is validated in section 3.4. Finally, conclusions on the acquired simulation model with truck platooning functionality are drawn in section 3.5.

3.1 Automated driving model specification

Given the conclusions from the literature study, a multi-anticipative (C)ACC controller using a constant time gap strategy is implemented in MOTUS to automate the longitudinal driving of equipped trucks. Cruise control is implemented to be used if there is no predecessor or if the predecessor is out of the sensor range. For the platoon leaders and for equipped trucks with a non-equipped predecessor, CACC functionality is reduced to ACC functionality. Platoon members only communicate with their immediate equipped predecessor. A collision avoidance system is implemented to guarantee collision-free driving in critical conditions.

3.1.1 System dynamics

These choices result in the controller framework given in Table 3.1. The choice for this specific controller is justified by verification of its performance as will be shown in section 3.4. The model parameter settings were obtained from the literature study, then tuned and verified in section 3.3 and 3.4 respectively, which results in the model parameter settings given in Table 3.2. Multiple desired time gap settings are chosen as part of the experimental design and will be further elaborated on in section 4.2.2. The control parameter for the relative speed error depends on the desired time gap setting and consequently also has multiple settings. This is explained in section 3.3.

Table 3.1: Applied (C)ACC controller.

Controller	Function
ACC	$a_{i,t}^{car-following} = k_s (s_{i,t} - s_{i,des,t}) + k_{\Delta v} R(s) (v_{i-1,t} - v_{i,t})$
CACC	$a_{i,t}^{car-following} = k_s (s_{i,t} - s_{i,des,t}) + k_{\Delta v} R(s) (v_{i-1,t} - v_{i,t}) + k_a a_{i-1,t}$
with:	$s_{i,des,t} = v_{i,t} t_{des} + s_0$ $R(s) = \frac{-1}{1 + Qe^{-\left(\frac{s}{P}\right)}} + 1$ $a_{i,t}^{cruising} = k_v (v_{des} - v_{i,t})$ $a_{i,t} = \min(a_{i,t}^{cruising}, a_{i,t}^{car-following})$

Table 3.2: Applied parameter values (C)ACC controller.

Parameter name	Symbol	Value
Standstill distance [m]	s_0	3
Desired time gap ACC [s]	t_{des}	1.5
Desired time gap CACC [s]	t_{des}	0.3-0.9, see section 4.2.2
Control parameter cruise control	k_v	0.3
Control parameter gap error	k_s	0.18
Control parameter relative speed error	$k_{\Delta v}$	1.93-3.52, depending on t_{des} , see section 3.3
Aggressiveness coefficient collision avoidance function	Q	20
Perception range coefficient collision avoidance function	P	40

In MOTUS, the vehicles' speed and longitudinal position are updated every time step according to **equation (3.1) and (3.2)**, using the desired acceleration from the (C)ACC controller of Table 3.1 as input. The time interval for the acceleration update, or the simulation time step, is 0.2 s, equal to the applied communication delay as indicated in section 2.1.7 of the literature study. The lateral position is only updated if a decision to change lanes has been made.

$$v_{i,t+1} = v_{i,t} + a_{i,t}\Delta t \quad (3.1)$$

$$x_{i,t+1} = x_{i,t} + v_{i,t}\Delta t + \frac{1}{2}a_{i,t}\Delta t^2 \quad (3.2)$$

Where:

$v_{i,t+1}$: speed of vehicle i at time $t+1$ [m/s]

$x_{i,t+1}$: position of vehicle i at time $t+1$ [m]

Δt : time interval for the acceleration update [s] = 0.2 s

$a_{i,t}$: desired acceleration of vehicle i at time t as calculated with the (C)ACC controller [m/s²]

3.2 Automated driving model implementation

The proposed (C)ACC controller is implemented in MOTUS for equipped trucks. An explanation of the design choices made for the automated driving is given in section 3.2.1. Adaptations to the human driving behaviour are also made to account for behavioural adaptation of drivers in the presence of truck platoons. These behavioural adaptations are briefly explained in section 3.2.2. An elaborate description of the structure of MOTUS and how the model functionality was extended is given in **Appendix D**. The new decision structure of the longitudinal driving behaviour of both equipped and non-equipped vehicles that has been implemented in MOTUS is schematized in Figure 3.1.

3.2.1 Automated driving for truck platoons

Several important design choices for the automated driving of truck platoons have been made. A more detailed and justified description of these design choices is given in **Appendix D**.

- **Equipped trucks will always drive automatically.**

The trucks that are equipped with AD technology will always drive automatically in longitudinal direction. Depending on whether the predecessor is also an equipped truck, the proximity of that predecessor and whether the maximum platoon size has already been reached, the equipped truck will either use ACC or CACC functionality. When using ACC, the equipped trucks will apply the same desired time gap as non-equipped trucks (see section 4.1.2). Although part of the equipped trucks might not always drive automatically in reality since this is a decision made by human drivers, the assumption that they are enables researching truck platooning to its full potential and allows discarding researching driver decisions on using (C)ACC functionality. This is defensible since the usage of (C)ACC functionality is also already captured in the penetration rate of truck platoons (see section 4.2.4).

- **Automated driving is only applied for longitudinal driving.**
Lane change decisions are still only made by the human truck drivers. Therefore the safety of a lane change is still evaluated based on the acceleration calculated with the IDM+ car-following model and the LMRS lane change model that are standard in MOTUS. A schematic overview of the LMRS decision structure is given in Figure D.2 of **Appendix D**. This ensures realistic lane change decisions, because the required deceleration of the putative follower in the target lane that is considered when making a lane change decision is still calculated with a human driving model.
- **Platoon formation takes place in the network ('on-the-fly').**
Platoons are only formed after vehicle generation. This is because the vehicle generator cannot distinguish whether the platooning conditions are satisfied before vehicles exist. The road network used (see section 4.1.1) is therefore long enough to make sure the truck platoons have been formed before reaching the on-ramp. The resulting compositions of the truck platoons once they have reached the on-ramp is elaborated on in section 5.1.1.
- **Equipped trucks only initiate platoon formation if their predecessor is close enough.**
An equipped predecessor is considered close enough if the inter-vehicle time gap is smaller than the sensor detection range (approximately 300 m) and if the estimated time it takes to complete a platoon formation manoeuvre is acceptable, i.e. is no longer than a few minutes (see also **Appendix D**). If the predecessor is out of this range, the considered vehicle will apply the ACC controller.
- **Equipped trucks initiate platoon formation by catching up with their equipped predecessor.**
Having the potential platoon follower speed up instead of the potential platoon leader to slow down prevents negative effects of truck platooning caused by lower average speeds of trucks. Although the legal speed limit might be slightly exceeded because of this, in the future such a catch-up manoeuvre might become legal to prevent these negative effects on traffic flow. This design choice will not have an impact on merging problems at the on-ramp since platoon formation will already be completed before reaching the on-ramp. The catch-up speed is slightly higher than the normal desired speed and stochastic (90 ± 1 km/h) so that it matches variability in vehicle driving behaviour as observed in reality.

The next two important design choices have implemented some flexibility in the simulation framework with respect to the driving behaviour of the truck platoons. These two functionalities can either be turned on or off for the simulations. They are further explained by the definition of the simulation scenarios as part of the experimental design in section 4.2.

- **The function that truck platoon members can create gaps ('yield') for other vehicles can either be turned on or off.**
When this function is turned off, platoon members will not yield for merging vehicles at the on-ramp if they notice an urgency to merge. The platoon will thus never be disengaged on the initiative of one of the platoon members. This allows researching the effects of truck platooning at the on-ramp on the merging behaviour. If simulation results show merging problems at the on-ramp because of this restrictive driving behaviour of truck platoons, the yielding function can be turned on in other simulations to determine to what degree this can solve merging problems. In the flow chart of Figure 3.1, the yielding function is turned off.
- **The function that truck platoon members can perform discretionary or cooperative lane changes can either be turned on or off.**
When this function is turned off, none of the platoon members is allowed to perform discretionary or cooperative lane changes once a platoon has been formed. As long as the platoons remain intact none of the platoon members will therefore change lanes to be able to

maintain their desired speed or to create a gap for merging vehicles. This allows researching the effects of truck platooning in the right lane at the on-ramp on the merging behaviour. Again, if simulation results show merging problems at the on-ramp because of this restrictive driving behaviour of truck platoons, the lane change function can be turned on in other simulations to determine to what degree this can solve merging problems. In the flow chart of Figure 3.1, the lane change function is turned off.

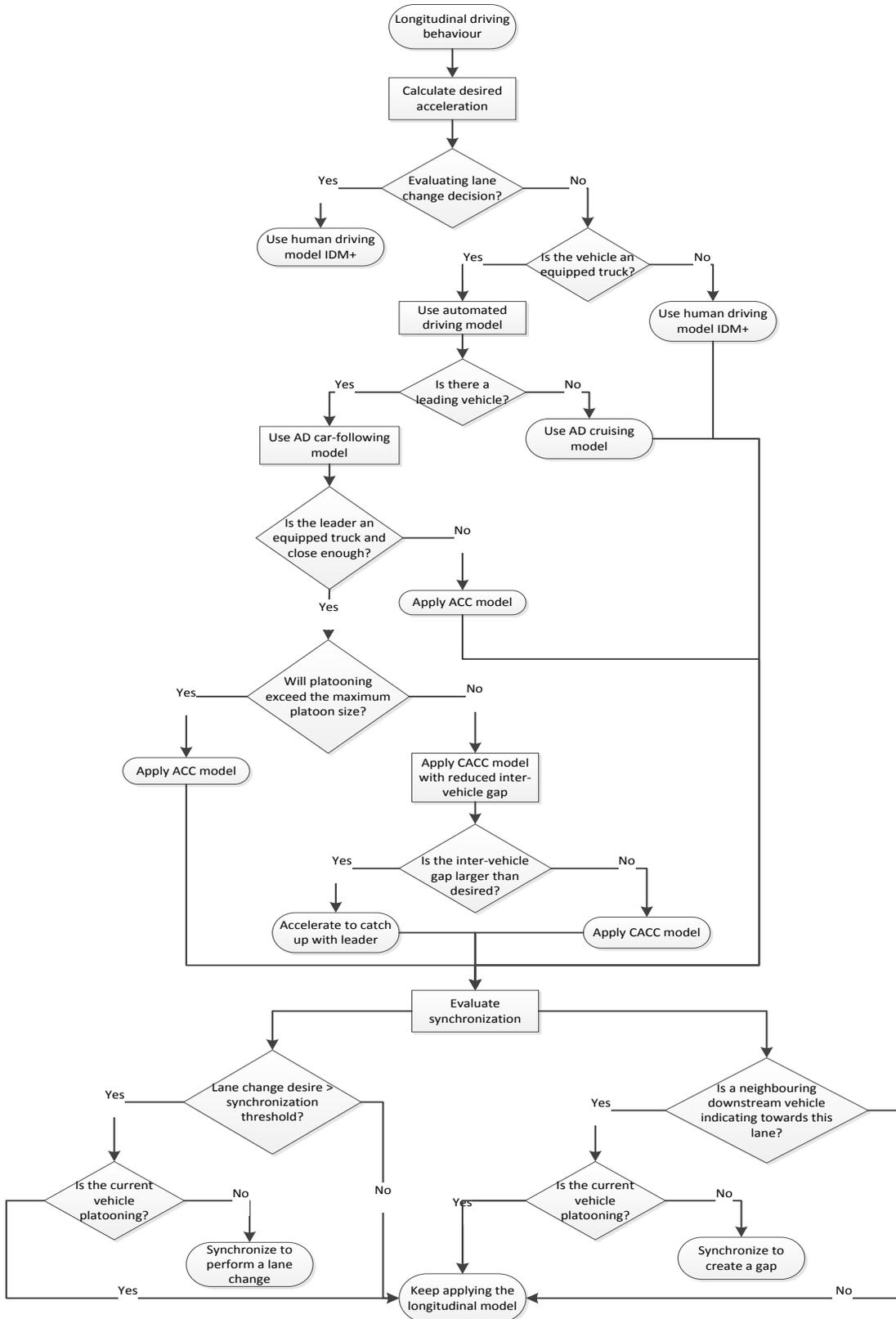


Figure 3.1: Flow chart of the longitudinal driving behaviour as implemented in MOTUS.

3.2.2 Behavioural adaptation

The driving behaviour of the human drivers in the simulations is only slightly adapted with respect to the lane change behaviour. Based on the empirical evidence on behavioural adaptation in the presence of truck platoons as described in section 2.3, **human drivers accept slightly smaller gaps than normal when changing lanes towards a lane with an equipped truck**. Although the empirical evidence is for non-automated truck platoons, it is likely that the effect for automated truck platoons is even larger. If merging drivers know they are dealing with an automated truck, they might know that its systems will always intervene to prevent a collision. Therefore merging drivers may start taking more risk by accepting a smaller gap when merging in front of an equipped truck. When evaluating a lane change decision, a lane change by human drivers is therefore now executed when the resulting gap with the putative equipped follower is no less than 0.3 s (normally 0.56 s). This minimum gap is only accepted if the merging vehicle's lane change desire is largest, i.e. it is near the end of the acceleration lane. In case of an emergency braking manoeuvre at this exact moment, this would just be enough to prevent a collision of the equipped truck with its new leader as will be shown in section 3.4.1. This design choice is further supported by human evaluation of gap acceptance observed in practice as well as by empirical evidence of on-ramp merging behaviour as explained in **Appendix D**. The resulting gap acceptance of merging vehicles is given in Figure 3.2.

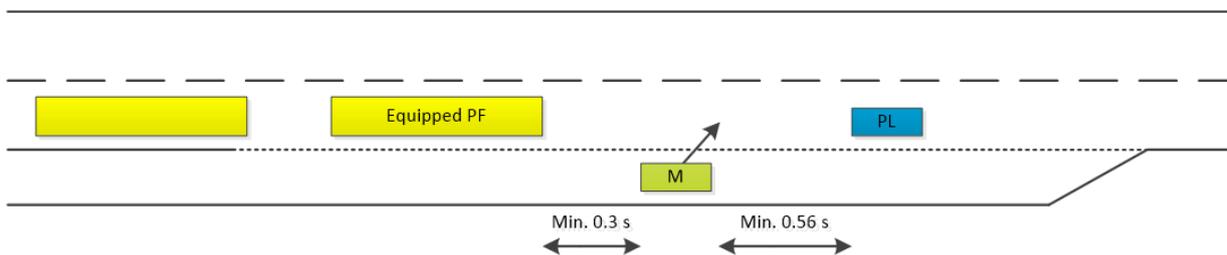


Figure 3.2: Gap acceptance of a merging conventional vehicle (M) when the putative follower (PF) is an equipped truck.

3.2.3 Conclusions

The proposed (C)ACC controller is implemented in MOTUS. In the initial simulation scenarios that will be run, truck platoons do not yield for merging vehicles so that they will remain intact when passing the on-ramp. Neither will they perform discretionary or cooperative lane changes. If simulation results indicate merging problems caused by this driving behaviour, these two constraints can be omitted to research platoon yielding and courtesy lane changing as possible solutions for merging problems. These platooning strategies will be further explained in section 4.2.1. Behavioural adaptation of merging vehicles is accounted for by having the merging vehicles accept a slightly smaller gap when merging within or in front of a truck platoon. The adaptations give a flexible simulation framework for analysis of truck platooning in mixed traffic.

3.3 Automated driving model parameter choice

This section describes how the parameter values of the proposed (C)ACC controller were chosen. Initially, the standard parameter values found in the literature study (section 2.1) were applied in simulation test runs as described in the next section 3.4, but the performance of the controller with these values proved insufficient. Therefore, tuning of the control parameters was necessary to generate plausible driving behaviour. The controller parameter values were tuned based on string stability and resemblance with human driving behaviour. A string stability constraint is used to guarantee collision-free driving and the acceleration response is matched to that of human drivers' response so that smooth and predictable driving behaviour results.

The control parameter for the gap error k_s of the (C)ACC controller given in Table 3.2 has already been calibrated such that the acceleration response will not overshoot and oscillate (Mullakkal-Babu et al. 2016). Therefore this parameter value should not be changed if one wants to maintain plausible driving behaviour. The control parameters of the collision avoidance function however can be changed without introducing overshoot and oscillation. The aggressiveness coefficient Q is determining for the strength of the braking response at small time gaps. When Q is changed, the perception range coefficient P should be adapted as well if necessary, so that the acceleration response still matches

that of a human driver. Another option is to adapt the control parameter for the relative speed error $k_{\Delta v}$. However, it may not be smaller than its standard calibrated value of 1.93 (Mullakkal-Babu et al. 2016) to prevent overshoot and oscillation of the acceleration response.

The proposed controller should therefore be made stable by changing the parameter values of Q , P and $k_{\Delta v}$. In (Mullakkal-Babu et al. 2016) the stability criterion for the proposed controller was derived for the ideal case without system delay. This criterion is used to derive the values of aforementioned parameters for which the controller is stable. Thereby an equilibrium speed of 90 km/h is assumed, matching the maximum vehicle speed of the trucks.

It was found that a parameter value above 20 for Q is not useful as the change in acceleration response rate above this value becomes negligible. A Q value of 20 gives a plausible acceleration response when P has a value of 40. Therefore these are chosen as the parameter values of the collision avoidance function to ensure the most adequate braking response in critical conditions.

The minimum threshold time gaps for string stability are derived for CACC gaps of 0.3, 0.5 and 0.7 s. For the gaps of 0.3 and 0.5 s, changing the values of Q and P alone was not sufficient and the value of $k_{\Delta v}$ also had to be increased to guarantee stability. For the gap of 0.7 s only the values of Q and P needed to be changed to achieve stability.

The controllers in the controller test scenarios have a system delay of 0.2 s. To ensure a safety margin, the values of $k_{\Delta v}$ were therefore increased by 10%, resulting in the values displayed in Table 3.3. This was found to be a reasonable increase to achieve a small safety margin; higher values did not result in a significant increase in safety margin anymore.

Table 3.3: Tuned parameter values of the (C)ACC controller to achieve stability under ideal conditions, increased with a safety margin ($v=90$ km/h).

Time gap [s]	Q	P	$k_{\Delta v}$
0.3	20	40	3.52
0.5	20	40	2.10
0.7	20	40	1.93

The acceleration responses with the old and new parameter values are given in Figure 3.3. As can be seen, the tuned responses are still smooth like a human driver's but ensure firmer braking at small gaps. Also, the range considered is kept around 300 m, corresponding to the sensor range of the equipped trucks.

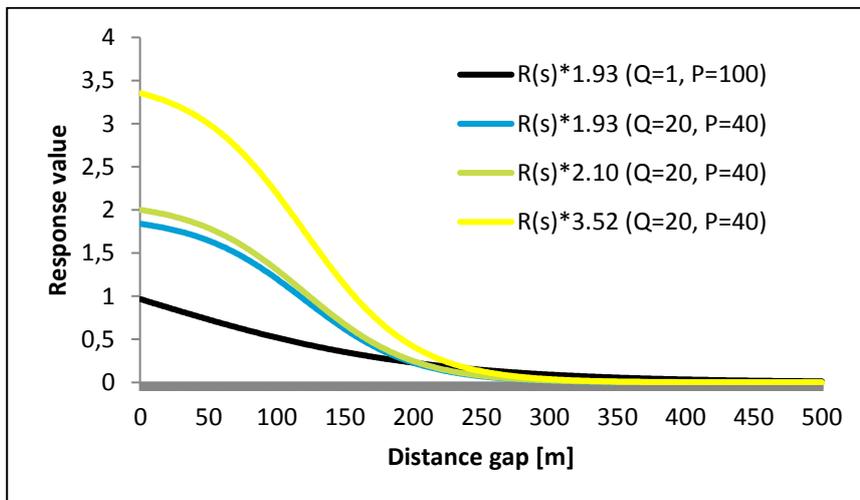


Figure 3.3: Acceleration responses with old and new parameter values.

The automated driving behaviour outside of the sensor range is covered by cruise control functionality. The acceleration response in these free driving conditions depends on the value of the cruise control parameter k_v . As stated in section 2.1.5, its value is generally set to 0.3-0.4. In this research the cruise control parameter value is therefore set to 0.3. All tuned parameter values of the applied (C)ACC controller are given in Table 3.2. The tuned (C)ACC controller is able to generate plausible driving behaviour, matching a human driver's acceleration response and attenuating disturbances and overshoot of the acceleration response. The performance of the tuned controller can now be verified by applying it for single-lane typical driving scenarios and for a two-lane motorway section with on-ramp in mixed traffic in MOTUS, which is described in the next section.

3.4 Automated driving model performance

Verification of the performance of the (C)ACC controller has been done by verifying the driving behaviour of a single truck platoon in several single-lane typical driving scenarios using a Matlab (MathWorks 2015) script and by verifying the driving behaviour of truck platoons in mixed traffic in MOTUS simulation test runs on a two-lane motorway section with on-ramp, as described in section 3.4.1 and section 3.4.2 respectively.

3.4.1 Typical driving scenarios

Several single-lane typical driving scenarios are defined that represent typical motorway traffic situations: a normal driving, stop-and-go, emergency braking, cut-in, cut-out, approaching and longer platoon scenario. Initially, the standard control parameter values as found in the literature study were applied to determine the performance of the controller. The tuned parameter values of Table 3.2 and Table 3.3 were also applied to test the performance of the tuned controller, showing improved performance in critical conditions. A detailed description of the typical driving scenarios as well as the standard control parameter values and vehicle capability settings used are given in **Appendix E**.

If not stated otherwise, the scenarios are run with truck platoons consisting of three trucks, corresponding to the largest maximum platoon size that is simulated in this study (see section 4.2.2). The desired time gap for CACC is set to 0.3 s, corresponding to the smallest gap size that is simulated in this study (see section 4.2.2), while the desired time gap for ACC is set at a relatively low value of 1 s. Each scenario is run multiple times to include a run with the collision avoidance system, a run in which the control is transitioned to the human driver if necessary and a run in which there is no additional safety mechanism (the 'standard' controller). The runs are performed with both single predecessor anticipation and multiple predecessor anticipation. The scenarios are executed using a simple Matlab (MathWorks 2015) simulation. It calculates the updated speed and positions of each vehicle based on the desired acceleration as in **equation (3.1) and (3.2)**, subject to vehicle acceleration and deceleration capability constraints and given the initial speed and position.

Test results

The performance of the controllers is different depending on the presence of the collision avoidance system or transition of control to the human driver. The graphs with the acceleration and speed profiles with corresponding inter-vehicle gaps of all scenarios and controllers can be found in **Appendix E**.

Standard controller

The proposed controller without collision avoidance system or transition of control has difficulty with situations in which hard braking is necessary. In all scenarios in which the platoon is driving behind a predecessor that suddenly brakes, the standard controller fails to prevent a collision. It is clear that in such situations the standard controller is not sufficient to guarantee collision-free driving. Only in the normal scenario it gives appropriate driving behaviour. Using multiple predecessor anticipation (MPA) could not improve the results, since it is always the platoon leader that crashes. With MPA, the 2nd platoon follower does show a slightly smoother acceleration response, but the benefit is almost negligible.

Controller with collision avoidance system

In all scenarios except the cut-in scenario, the proposed controller with collision avoidance system and the standard control parameter values (Table E.1) results in feasible driving behaviour in which collisions are avoided, as is illustrated in Figure 3.4. It must be noted though that in the emergency

braking scenario, the controller fails to prevent a collision if the braking rate of the platoon predecessor is increased above -4 m/s^2 . This is because the trucks can only brake at -4 m/s^2 , while the platoon predecessor is a passenger car that can brake at -6 m/s^2 . If the predecessor brakes at the maximum braking rate during the longest possible period of time, namely from full speed (90 km/h) to zero (the worst case possible), a collision is then obviously inevitable. However, in practice such a situation is very unlikely to occur and if it does, it is likely that the trucks will make an evasive manoeuvre in lateral direction in time. Therefore this can be considered a safety issue with very low risk. A similar line of reasoning can be applied to the performance in the cut-in scenario, since it is highly unlikely that a vehicle will accept a gap of 0.3 s in reality and it will certainly not happen in simulation, as is explained in section 3.2.2.

When the controller with tuned parameter values was applied to the emergency braking and the cut-in scenario, it was observed that the performance of the controller is further improved as collisions no longer occur, although the minimum observed gap was 0 m. Even in the most extreme scenario of a predecessor braking at -6 m/s^2 to standstill, the platooning trucks will then not collide. Its performance is sufficient even at the smallest CACC time gap of 0.3 s.

Controller with transition of control

Interestingly, the controller with transition of control performs even worse than the standard controller in all scenarios. For example, in the stop-and-go scenario, not only the platoon leader crashes with its predecessor, but also the followers. The platoon followers only do not crash if the CACC time gap is set to 0.7 s or higher (see **Appendix E**). Another example is the approaching scenario, where the platoon only does not crash with its predecessor if the speed difference is 25 km/h or less, whereas this is 85 km/h for the standard controller (also shown in the appendix). Apart from these findings, it is also disputable whether the time it takes to transit the control back to the human driver is indeed 1 s. Research indicates that the time it takes for human drivers to become aware of the situation and judge on what to do is often underestimated and should be more in the order of tens of seconds (Lambers 2017). It is therefore concluded that the controller with transition of control is not a viable option for safe driving.

Oscillations and overshoot of the acceleration response

Apart from testing the ability to prevent a collision, the smoothness of the acceleration responses of the controllers is also important to generate plausible driving behaviour. In all scenarios, the tuned controller resulted in smooth driving behaviour in which oscillations are damped and overshoot of the response is prevented. This confirms the validity of the parameter values.

Multiple predecessor anticipation (MPA) could be a way to further improve the performance of the proposed controller. However, the test results show that it is always the platoon leader that crashes in the scenarios and not the follower(s). This means using MPA is not useful to improve the performance of the controller for the platoon leader, as it has no effect on the platoon leader. In the case of a maximum platoon size of three vehicles, only the 2nd follower benefits from MPA by somewhat smoothing the acceleration response, but the benefit is negligible and no extra collisions are prevented in the typical driving scenarios. However, the added value of MPA can be large for longer platoons of many vehicles as is shown in the longer platoon scenario graphs in **Appendix E**. Here it is clearly visible that the acceleration responses of the platoon followers become much smoother. The potential of MPA to decrease overshoot and reduce oscillations is clearly visible. Because the testing revealed that using MPA would have no effect on the occurrence of collisions and its added value is limited when a maximum platoon size of three trucks (see section 4.2.2) and a communication delay of 0.2 s (see section 3.1.1) are considered, MPA is not used in the controller that is implemented in MOTUS.

Conclusions

Given the test results, the (C)ACC controller with collision avoidance system is chosen as the controller to implement in MOTUS. It has proven to be much safer than the standard controller and the controller with transition of control in critical conditions while still having a smooth acceleration response, similar to human drivers. Platoon members will only anticipate on their immediate predecessor and not multiple predecessors since MPA will not result in fewer collisions and the added value is very limited when a maximum platoon size of three trucks is considered.

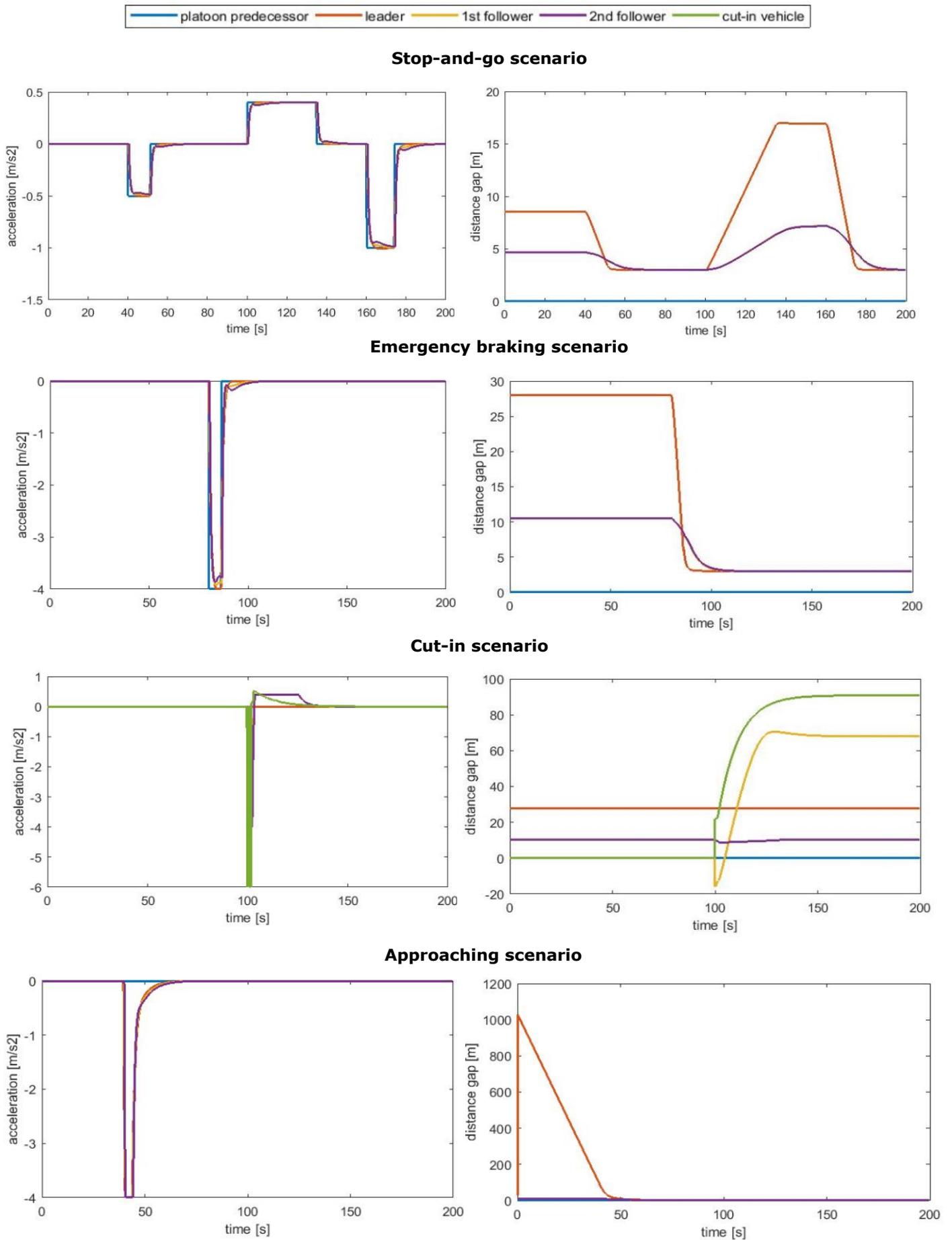


Figure 3.4: Performance of the proposed (C)ACC controller with collision avoidance system in typical driving scenarios.

3.4.2 Motorway with on-ramp in MOTUS

Apart from the single-lane typical driving scenarios, the performance of the proposed controller was also verified in simulation test runs in MOTUS for a two-lane motorway with on-ramp in mixed traffic. This allows verifying the validity of the driving behaviour of the truck platoons in interaction with human drivers in a more complex two-lane network. Moreover, it allows verifying the validity of the standard MOTUS model parameters and the changes proposed to these standard values due to behavioural adaptation as described in section 3.2.2.

Initially, the MOTUS test runs were performed with the (C)ACC controller with the standard control parameter values (see Table E.1 in **Appendix E**) that follow directly from the literature study (section 2.1). The tuned parameter values of Table 3.2 and Table 3.3 were also applied to test the performance of the tuned controller. The performance was judged by searching for collisions of equipped trucks and observing the driving behaviour in the GUI. In order to check the performance in free flow conditions as well as in congestion, in the simulation test runs a dynamic demand was used. It was chosen such that both free flow and congestion are observed. This includes the onset of congestion and the solving of congestion. Special attention is paid to the extent to which the merging behaviour displayed by human drivers is realistic. The network used is equal to the network that is used in the actual simulations. A description of the road network used is given in section 4.1.1 and a description of the set-up of the simulation test runs, including the dynamic demand, is given in section D.3 of **Appendix D**.

In the MOTUS simulation test runs, for the human car-following model IDM+ and the lane change model LMRS, the standard parameter values were used, except for the gap acceptance of merging vehicles when interacting with truck platoons (see section 3.2.2). These standard parameter values were calibrated and validated for a Dutch motorway by (Schakel et al. 2012). The validity of the adapted simulation model MOTUS with truck platooning was tested by comparing the results of the simulation test runs with the standard calibrated and validated model without truck platooning as well as comparing the results with empirical evidence.

Test results

During the simulation test runs with the standard control parameter values, multiple collisions of equipped trucks with their predecessor were observed. These occurred when a traffic jam had formed at the on-ramp area and when they had to brake quite hard. The collisions are more widespread and severe as the desired CACC time gap decreases. With the collision avoidance system turned off, the number and severity of collisions was higher than with the system turned on. When it was off, equipped trucks could even collide severely with non-equipped predecessors.

Apparently the controller with standard parameter values is not able to handle situations with sudden braking well, especially when driving at small time gaps. This is in line with the findings from literature on the performance of the proposed (C)ACC controller as described in section 2.1.6. The observations are also in line with the findings of the verification of the controller's performance in typical driving scenarios as described in the previous section, where it is observed that a controller with collision avoidance system indeed manages to handle critical situations better than a controller without it, but still cannot handle the most extreme situations with the standard parameter values. However, different from what one might expect given the verification of the controller's performance in typical driving scenarios as described previous section, the controller with collision avoidance system performs worse than in those single-lane typical driving scenarios. This is caused by the more complex driving behaviour in MOTUS: the interaction with the lane change model LMRS is not captured by the controller verification in the typical driving scenarios. Therefore adaptations to the standard (C)ACC model parameter values were necessary to ensure a stronger braking response.

When the tuned parameter values of section 3.3 were applied in the simulation test runs, it was found that the controller can now generate smooth driving behaviour while preventing collisions in critical conditions, similar to the results found in the single-lane typical driving scenarios. The interaction with human drivers was validated by showing that the performance of the adapted simulation model is similar to the performance of the standard calibrated and validated version of MOTUS. A full description of the validation of the adapted simulation model MOTUS is given in **Appendix D**. Therefore, the standard calibrated IDM+ and LMRS model parameters are kept and will be applied in the simulations. The fact that the standard calibrated and validated parameter values of the human driving behaviour models will be used in the MOTUS simulations is a crucial aspect of the research,

since the use of the calibrated and validated model parameters proves the validity of the simulations performed in this study.

3.5 Conclusions

A (C)ACC controller using a constant time gap strategy with single predecessor anticipation and a collision avoidance system is implemented in MOTUS to serve as longitudinal controller for equipped trucks (Table 3.1). The implementation has been executed in such a way that different platooning strategies can be applied, which will be further explained in section 4.2.1. Behavioural adaptation was implemented in MOTUS by adapting the human driving behaviour such that the minimum accepted gap of merging vehicles is smaller when changing lanes towards an equipped truck.

After tuning of the control parameters, the controller is able to generate safe driving behaviour in critical conditions and gives a smooth acceleration response. Disturbances in and overshoot of the acceleration responses are attenuated. An overview of the tuned parameter values of the controller is given in Table 3.2.

Validation of the proposed (C)ACC controller with tuned parameter values was done by verifying its performance for single-lane typical driving scenarios and for a two-lane motorway section with on-ramp in mixed traffic in MOTUS. For the human driving behaviour models of MOTUS, IDM+ and LMRS, the standard parameter values were used, which were calibrated and validated for a Dutch motorway. An exception to this is the smaller minimum accepted gap of drivers when changing lanes towards an equipped truck. The validity of the adapted simulation model was tested by comparing the standard simulation model without truck platooning with the adapted simulation model with truck platooning. Additional empirical evidence was also used to test the validity of the adapted simulation model (**Appendix D**). The performance of the adapted simulation model was thereby verified. The next step in the research is to apply the acquired simulation framework, but to do so the experimental design of the simulations first needs to be determined.

4 Experimental design

Chapter 3 has provided us with a validated simulation model that is able to simulate truck platoons. The next step is to define the traffic scenarios that are going to be analysed. For this, simulation scenarios are defined. Both simulation scenario constants and simulation scenario variables are distinguished. The constants are the fixed design choices, i.e. the variables that do not change for different simulation scenarios. The variables are those that do differ per scenario. The fixed design choices are first discussed in section 4.1. Next, the simulation scenario variables are explained in section 4.2. This gives insight into the platooning and traffic variables to be analysed and the resulting number of scenarios. To be able to compare the performance of the different scenarios, performance indicators are then chosen in section 4.3. Both traffic performance and traffic safety indicators are used. Finally, conclusions on the scenarios and indicators are drawn in section 4.4.

4.1 Simulation scenario constants

Several fixed design choices are made that are the same for all simulation scenarios. The most important one is the design of the road network, but the ACC gap maintained by the equipped trucks is also fixed.

4.1.1 Road network

The road network has the characteristics of the A67 between Eindhoven and Venlo in the Netherlands. This motorway represents one of the busiest freight routes in the Netherlands and among others is a very important connection from for instance the port of Rotterdam and Antwerp to the hinterland. This makes it a suitable stretch of motorway to analyse the potential of truck platooning (Bakermans 2016). The road network used in all the simulations therefore meets the following design choices:

- It represents a two-lane motorway section with an on-ramp.
- The speed limit matches that of the A67 Eindhoven-Venlo: 130 km/h.
- The length of the acceleration lane is 350 m according to the Dutch design standards (Rijkswaterstaat 2015).
- Vehicles on the motorway and on the on-ramp can already see each other approximately 100 m before the start of the acceleration lane to allow for anticipation.
- The motorway section has a length sufficient to capture effects on traffic flow dynamics and complete platoon formation.

A road network was designed in MOTUS according to these choices. The simulated road network has a total length of 6350 m. There is a 4000 m warm-up stretch followed by a 350 m section starting from the start of the acceleration lane. After this area, there is another 2000 m stretch downstream of the acceleration lane area. These lengths make sure that effects of the on-ramp in upstream and downstream direction can be noticed. The stretch upstream of the on-ramp is longer than the stretch downstream because additional length is needed upstream to make sure platoon formations have completed before reaching the on-ramp. It also allows traffic to settle after vehicle generation. Virtual loop detectors are placed on the motorway every 200 m, starting from 2 km upstream of the acceleration lane until 2 km downstream of the acceleration lane. On the acceleration lane itself, loop detectors are placed every 50 m to allow for more precise analysis of merging behaviour. Vehicles on the motorway and the on-ramp can see each other starting from 100 m upstream of the start of the acceleration lane, matching the required sight length according to the Dutch design standards (Rijkswaterstaat 2015). On the first 50 m of on-ramp, the speed limit is 50 km/h so that the acceleration behaviour on the acceleration lane is realistic. An aerial view of the on-ramp area of the resulting network is displayed in Figure 4.1.

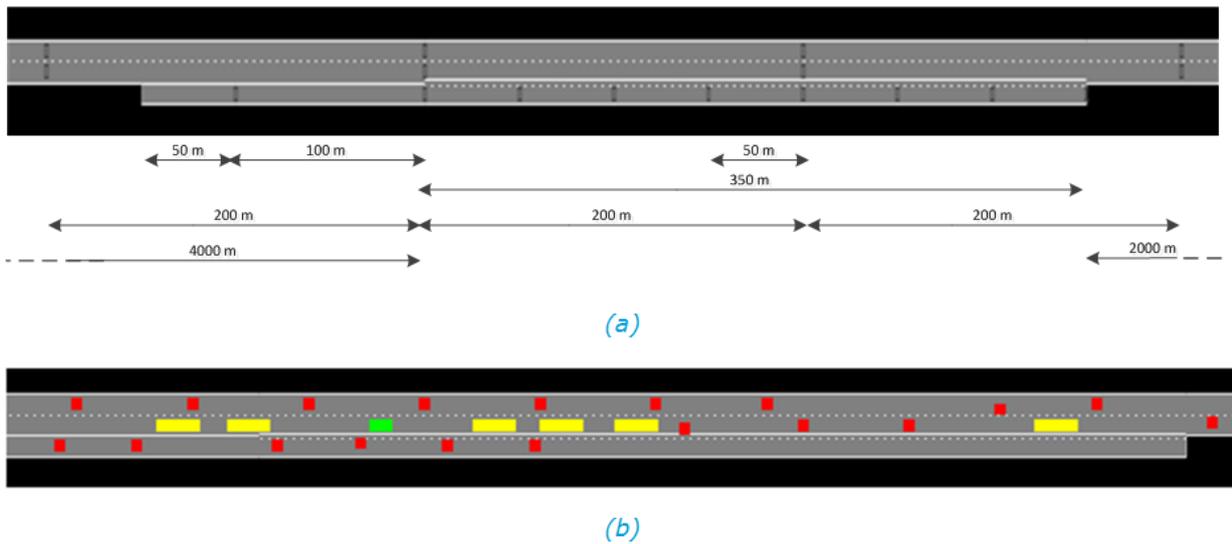


Figure 4.1: Aerial view of the on-ramp area of the road network with detector locations and dimensions (a) and detailed view of traffic at the acceleration lane with truck platoons (b).

4.1.2 ACC gap

Given these considerations and findings of section 2.1.4 of the literature study, the ACC gap is set at **1.5 s**. When not platooning, this will thus be the desired gap applied by the equipped trucks.

4.2 Simulation scenario variables

The simulation scenarios to be applied will differ on several aspects. Three different platooning strategies are distinguished in section 4.2.1: fixed gaps, allow yielding and allow lane changing. Moreover, different platoon configurations are considered in section 4.2.2: two different maximum platoon sizes and four different desired CACC inter-vehicle gaps. Also, four different traffic intensities are distinguished as described in section 4.2.3: low traffic, medium traffic, heavy traffic and congestion. The penetration rate of equipped trucks may have four different values as explained in section 4.2.4. An overview of the resulting simulation scenario design is given in the conclusions in section 4.2.5.

4.2.1 Platooning strategies

Three different platooning strategies are distinguished. The first two platooning strategies considered are different in whether the CACC inter-vehicle gaps between the trucks in the platoons are influenced by other traffic or not. The third platooning strategy is different by the fact that lane changes of platoon members are allowed. How the strategies were implemented in MOTUS is described in section 3.2.1. The strategies that can be distinguished thus are:

1. **Fixed gaps**
2. **Allow yielding**
3. **Allow lane changing**

In the first strategy, the inter-vehicle gaps of the platoon are fixed in the sense that they do not adapt the gap to create room for merging vehicles. The second strategy is a strategy in which the trucks in the platoon may gradually increase the gaps with their predecessors when a vehicle wants to merge at the on-ramp, depending on the lane change desire of the merging vehicle. This yielding for merging vehicles is similar to what human truck drivers might do (see Figure 3.1). The third and final strategy is a strategy in which platoon members do not yield for merging vehicles, but may perform courtesy lane changes to create room for merging vehicles if possible. The second and third strategy will be applied in the simulations if simulation results indicate significant merging problems with the first strategy as will be addressed in Chapter 5. In this way it can be determined whether yielding or lane changing will reduce merging problems.

4.2.2 Platoon configurations

Within platoon configurations, two components are distinguished. Firstly, it may refer to the number of vehicles in the platoon. Secondly, it may refer to the CACC gap sizes adopted by the vehicles in the platoon.

Maximum platoon size

Considering the findings from sections 2.1.6 and 2.1.7 of the literature study in which reasons why the maximum platoon size is limited are given, the maximum platoon sizes chosen for the simulations will be based on the need to provide sufficient gaps for vehicles merging from the on-ramp as well as on what is considered acceptable for near-term deployment. This means that the maximum platoon sizes considered will be **two and three trucks**.

CACC gaps

To find out how the gaps affect the merging vehicles' driving behaviour, multiple gap settings are applied during the simulations.

From initial simulation test runs it was found that for desired gaps below approximately 0.87 s (excluding a standstill distance of 3 m), merging vehicles are not willing to merge in between the trucks of the platoon anymore. Thereby it is assumed that the trucks never cooperate when platooning (the 'fixed gaps' strategy), i.e. they never decelerate to create a gap for the merging vehicle, but proceed with constant speed. The CACC gaps are chosen below this value to prevent undesirable merging in the platoons.

Given the above consideration but also the findings from section 2.1.5 of the literature study, the smallest CACC time gap applied in this research will be **0.3 s**. Although user acceptance of such extremely small gaps might still be limited, choosing this value allows researching truck platooning to its full potential. Two larger values are also chosen: **0.5** and **0.7 s**. These have been chosen because 0.5 s is technically already possible and the minimum that is politically already acceptable (BAR Commissie and Rijkswaterstaat 2017, Cornelissen et al. 2017), while 0.7 has been chosen to be able to quantify the effects of slightly larger gaps.

Similar to the 'allow yielding' strategy, a CACC gap larger than the minimum accepted gap is also applied if simulation results indicate significant merging problems with the CACC gaps smaller than the minimum accepted gap. In this way it can be determined whether larger gaps will reduce merging problems. This gap is set at **0.9 s**.

4.2.3 Traffic intensities

In order to get a representative view of the effects of truck platooning on traffic performance and safety, four different traffic intensities are applied in the simulations. These represent three real-life cases for different times of day for an existing motorway and a scenario with congestion. This congestion scenario was added because no congestion occurs in any of the other empirical scenarios. The applied traffic intensity scenarios are:

- **Low traffic (during the late evening/night/early morning)**
- **Medium traffic (in the middle of the day)**
- **Heavy traffic (during rush hours)**
- **Congestion**

To determine representative intensities for these periods of the day, empirical data from the Rijkswaterstaat database INWEVA ("Intensiteiten op Wegvakken") (Rijkswaterstaat 2017) is used. This public data contains intensities of all motorways in the Netherlands, obtained from induction loops in the road surface. The data is given for different periods of the day to represent both peak periods and periods with lower traffic and for the vehicle classes passenger cars, light freight traffic (non-articulated vehicles) and heavy freight traffic (articulated vehicles, i.e. tractor-trailer).

The A67 between Eindhoven and Venlo in the Netherlands is chosen as a representative two-lane motorway section with heavy freight traffic. It represents one of the busiest motorways with respect to the share of freight traffic and is an important connection from the ports of Rotterdam and Antwerp to the German hinterland, making it very suitable for truck platooning (Bakermans 2016). From this

motorway section, the most recent data from 2016 is used to retrieve the desired intensities. Since there is no overtaking prohibition for trucks on this stretch of motorway to prevent platoon formation of non-automated trucks (Beenker and Reintjes 2012), no overtaking prohibition will be applied in the simulations either. A detailed explanation of the data analysis applied to retrieve the desired intensities is given in **Appendix F**. The resulting intensities are given in Table 4.1.

Table 4.1: Applied traffic intensities in the simulations.

Intensity		Low	Medium	High	Congestion	
Time of day		Early morning	Afternoon	Morning peak	-	
Motorway	Total [veh/h]	660	1178	2426	4000	
	Lane distribution [%]	Left	35	50	65	68
		Right	65	50	35	32
	Share of light trucks [%]	10.9	10.1	5.2	5.0	
	Light trucks [veh/h]	72	119	126	200	
	Share of heavy trucks [%]	45.3	29.7	14.5	20.0	
Heavy trucks [veh/h]	299	350	352	800		
On-ramp	Total [veh/h]	240	1171	982	1000	
	Share of light trucks [%]	5.8	5.2	6.3	5.0	
	Light trucks [veh/h]	14	61	62	50	
	Share of heavy trucks [%]	30.8	2.0	2.5	2.0	
	Heavy trucks [veh/h]	74	23	25	20	

4.2.4 Equipped truck penetration rate

Different penetration rates for the share of trucks that is equipped are chosen to be able to capture the effects of different numbers of platoons. The penetration rates chosen are **25, 50, 75 and 100%** to cover a wide range of possibilities so that all stages of the introduction of truck platooning are captured.

To be able to analyse the effects of truck platooning compared to a situation without truck platooning, base simulation scenarios without any platooning are also run. In these base scenarios, the penetration rate of equipped trucks is therefore 0%.

4.2.5 Conclusion on the simulation scenarios

All considered variables are combined in simulation scenarios. An overview of the simulation scenario variables with their considered values is given in Table 4.2.

Table 4.2: Overview of the simulation scenario variables.

Variable	Values				
Platooning strategy	Fixed gaps	Allow yielding	Allow lane changing		
Platoon configuration:					
Maximum platoon size	Two trucks	Three trucks			
CACC gaps	0.3 s	0.5 s	0.7 s	> min. accepted gap: 0.9 s	
Traffic intensity	Low	Medium	High	Congestion	
Equipped truck penetration rate	0% (base)	25%	50%	75%	100%

This results in a total number of 96 simulation scenarios with truck platooning if the 'allow yielding' and the 'allow lane changing' platooning strategies as well as the CACC gap larger than the minimum accepted gap are excluded. The base scenarios can only differ with respect to the traffic intensity and so there are only four base scenarios. This gives a total of 100 initial simulation scenarios. The platooning scenarios are also run with the 'allow yielding' and 'allow lane changing' strategies where relevant (see section 5.2), so that this increases to 292 scenarios. The inclusion of the CACC gap larger than the minimum accepted gap increases this number further up to 388 scenarios in total. Each simulation run represents one hour of traffic. The relevant scenarios are run with twenty replications per scenario (see **Appendix H** for how this was determined) on a computer with a 3.5 GHz quad core CPU and 64-bit OS, resulting in a computational time of approximately 2 to 5 minutes per scenario, depending on the number of vehicles in the network. A time step of 0.2 s (see section 3.1.1) is used.

4.3 Performance indicators

To assess and compare the performance of the scenarios in terms of traffic performance and traffic safety, performance indicators are used. The required data is obtained from the simulation output. MOTUS provides two options that are both used: data from the loop detectors and vehicle trajectory data. The detectors register every minute the number of vehicles that passed the detector as well as the average speed of those vehicles in the past minute. The vehicle trajectory data contains the time stamp, position, speed, acceleration, distance gap and relative speed with the predecessor per vehicle per second. Based on the possibilities of this data, traffic performance and safety indicators are chosen in sections 4.3.1 and 4.3.2 respectively. A description of how the required amounts of simulation output data per simulation scenario are determined and how this data is managed to obtain reliable performance indicator values is given in **Appendix H**.

4.3.1 Traffic performance indicators

To quantify the traffic performance of scenarios, the following traffic performance indicators are used. Macro level indicators are used to capture network effects and micro level indicators are used to capture effects on a specific area or (group of) vehicle(s). A more detailed description of the indicators including their mathematical definitions is provided in **Appendix G**.

Macro level indicators

The macro level indicators can be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical indicators

- **Speed- and flow-contour plots.** These give insight into the spatio-temporal developments of aggregate traffic speed and thereby in jam patterns and traffic flow dynamics.
- **Fundamental diagrams.** These give insight into the traffic states observed. They are given in the density-flow plane, the density-speed plane and the flow-speed plane. A distinction is made between the area upstream of the on-ramp, the on-ramp area and the area downstream of the on-ramp, so that differences in traffic states between these areas can be observed. A distinction is also made between the left and right lane to be able to observe differences in traffic states between the lanes.

Global value indicators

- **Total time spent (TTS)** in the network. The TTS is calculated from the vehicles' trajectories in the simulation by taking the sum of the time spent in the network by each individual vehicle over all vehicles generated during simulation. It gives an indication of network performance expressed in time. It is advantageous over a delay indicator since it does not require defining a base case without delay, which is subject to uncertainty.
- **Maximum outflow (QoutMax).** It is calculated by repeatedly calculating the average outflow during an aggregation period of five minutes using a moving average method that moves one minute per calculation and then taking the maximum calculated value. The aggregation period of five minutes prevents a bias in the result. Flow data from the most downstream detector is used. This method is similar to the FOSim method (Henkens and Tamminga 2015). It gives an

indication of road throughput so that possible capacity effects of truck platooning can be noticed.

- **Mean absolute speed difference across the lanes (dVLane).** The time mean speed is converted to space mean speed to correct for overestimation of means. dVLane gives an indication of the degree of inhomogeneity of traffic states across the lanes.

Micro level indicators

The micro level indicators can also be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical and global value indicators

- **Merging speed distribution.** This is a bar chart indicating the average merging speed observed for a specific part of the acceleration lane. It gives an indication of how well vehicles are able to synchronize their speed to the vehicles on the motorway and thereby the severity of disturbances in the traffic flow caused by the on-ramp.
- **Gap distributions of the on-ramp area.** These give insight into the interaction between the merging vehicles and vehicles on the motorway, among which are the truck platoons. Distinction is made between equipped trucks and other traffic. It gives an indication of the frequency of occurrence of small inter-vehicle gaps that might result in disturbances in the traffic flow.

4.3.2 Traffic safety indicators

To quantify the traffic safety of scenarios, the following surrogate safety indicators are used. Again, macro level indicators are used to capture network effects and micro level indicators are used to capture effects on a specific area or (group of) vehicle(s). An explanation of surrogate safety indicators as well as a more detailed description of the indicators including their mathematical definitions is provided in **Appendix G**.

Macro level indicators

The macro level indicators can again be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical indicators

- **Time to collision (TTC) distributions.** The time to collision is the time after which two vehicles will collide if they remain at their present speed and on the same lane. These give insight into the severity and frequency of occurrence of dangerous situations that may lead to collisions. They are studied for the on-ramp area to capture the interaction between the merging vehicles and the truck platoons, but also for the entire network to capture effects of truck platooning in upstream and downstream direction. Thereby the minimum TTC observed provides information on the most unsafe case that has taken place.

Global value indicators

- **Time-exposed TTC (TETTC) and time-integrated TTC (TITTC).** The TTC distributions are further analysed by calculating the time-exposed TTC as well as the time-integrated TTC. The former is the duration of time that the TTC is less than a threshold value and the latter is the total TTC summation during that time. A suitable threshold value is chosen based on the minimum value that is still considered safe. The truck platoons are excluded from the analysis to enable a fair comparison between scenarios.

TTC threshold value

The TTC threshold value should be chosen such that it distinguishes between safe and unsafe vehicle encounters based on the TTC values. In past research, different thresholds have been adopted varying from less than one to approximately 8 s (Charly and Mathew 2016, Mahmud et al. 2017). The threshold depends on the traffic conditions and driver behaviour parameter settings (Charly and Mathew 2016). For example, the presence of different vehicle classes has an effect on the threshold as well as the desired time gap of drivers. The threshold is typically lower for urban areas with intersections than for rural roads. Moreover, a threshold should

obviously not be chosen below the human reaction time (Mahmud et al. 2017). The threshold adopted in this study is 3 s since it is recommended for two-lane rural roads by (Farah et al. 2009, American Association of State Highway Transportation 2011, Mahmud et al. 2017).

Micro level indicators

The micro level indicators can again be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical and global value indicators

- **Merge location distribution.** This is a histogram indicating the frequency of occurrence of merge locations and its standard deviation. It gives an indication of how well merging vehicles are able to merge. Late merging or even inability to merge might lead to dangerous situations. If a vehicle is (almost) unable to merge, it is shown in the bar chart by the bar representing the end of the acceleration lane.
- **Merging speed distribution.** Apart from serving as a traffic performance indicator, the merging speed distribution also serves as a traffic safety indicator. It gives an indication of how well vehicles are able to synchronize their speed to the vehicles on the motorway and thereby reveals potentially dangerous situations caused by speed differences.

4.4 Conclusions

In the simulations, several variables are distinguished. Simulation scenarios can vary in platooning strategy (fixed gaps, allow yielding or allow lane changing for merging vehicles), platoon configuration (maximum platoon size 2 or 3 trucks, CACC gaps 0.3, 0.5, 0.7 s or 0.9 s), traffic intensity (low, medium, high or congestion) and penetration rate of equipped trucks (0, 25, 50, 75 or 100%). Thereby the 'allow yielding' and 'allow lane changing' strategies are applied for those scenarios in which merging problems with the fixed gap strategy occur. Similarly, the 0.9 s CACC gap, which is higher than the minimum accepted gap, is used in those scenarios in which merging problems occur, thereby allowing vehicles to merge in the platoon.

The performance of the scenarios is analysed by several performance indicators. They allow analysing traffic performance as well as traffic safety whereby indicators on macro (network) level as well as micro (vehicle) level are used. Overall performance of the network is given by global value indicators that cover different performance aspects: the total time spent in the network by all vehicles, the mean absolute speed difference across the lanes and the maximum outflow. Traffic patterns are revealed by graphical indicators such as speed- and flow-contour plots, fundamental diagrams and gap distributions. To analyse safety, surrogate indicators are used that tell something about the frequency and severity of the occurrence of an unsafe situation. These include time to collision indicators, the merge location distribution and the merging speed distribution. The indicators together should be able to give a complete picture of the performance and enable a balanced comparison of scenarios.

5 Simulation results

Given the adapted simulation model MOTUS of Chapter 3 as well as the simulation scenarios and performance indicators of Chapter 3, the next step is to simulate the simulation scenarios using the adapted model and evaluate the outcomes in terms of the performance indicators. The effects of truck platooning on traffic performance and safety are analysed in section 5.1 by comparing the base scenarios, the scenarios without truck platooning, to the corresponding platooning scenarios. Thereby the effects are researched for the case that truck platoons apply the strategy in which the inter-vehicle time gaps are fixed as explained in section 4.2.1. The differences in effects between the different platoon configurations, which are the two maximum platoon sizes and the three CACC time gap settings defined in section 4.2.2, are also elaborated on. Possible solutions to the merging problems caused by truck platooning as shown in section 5.1 are explored in section 5.2. These possible solutions are the two other platooning strategies, which are the strategy in which the platoons are allowed to yield for merging vehicles to create a gap and the strategy in which the platoons are allowed to perform courtesy lane changes to create a gap for merging vehicles, as defined in section 4.2.1. Another possible solution that is addressed in this section is a CACC time gap that is larger than the minimum accepted gap by merging vehicles, as defined in section 3.2.2. Lastly, a concluding summary of the impacts of truck platooning on traffic performance and safety as well as the differences between the platoon configurations and the platooning strategies is given in section 5.3.

5.1 Truck platooning effects

In this section, the effects of truck platooning as compared to the base scenarios are described. The performances are given for the different penetration rates of equipped trucks as well as for the different traffic intensities. The effects are given for the 'fixed gaps' platooning strategy in which platooning trucks are not allowed to yield for other vehicles nor to change lanes, so platoons remain intact and in the right lane at all times. The compositions of the platoons arriving at the on-ramp are first described in section 5.1.1. The effects of these truck platoons on the on-ramp merging behaviour are then given in section 5.1.2. The resulting traffic safety and performance on the motorway is elaborated on in section 5.1.3. Within these sections, details are given on the differences in effects between the different platoon configurations. These are the two maximum platoon sizes (2 trucks and 3 trucks) and the CACC time gap settings (0.3, 0.5 and 0.7 s) as determined in section 4.2.2. Conclusions are provided in section 5.1.4

5.1.1 Compositions of the platoons

Before the effects of truck platooning on the traffic performance and safety of the motorway are described, the compositions of the truck platoons arriving at the on-ramp area are now given to show how many platoons of what size arrive at the on-ramp area. These compositions are different for the different traffic intensities, the different penetration rates of equipped trucks and the allowed maximum platoon size (see section 4.2 for an overview of the applied simulation variables). A detailed overview of the resulting platoon compositions is given in **Appendix J**. Since the number of heavy trucks in the free flow simulation scenarios is hardly different, the platoon compositions are almost identical for the free flow scenarios. In the congestion scenarios, the number of platoons is only higher than in free flow at higher penetration rates. The platoon compositions in free flow for medium to high traffic intensities and in congestion are given in Figure 5.1.

The number of platoons passing the on-ramp increases with increasing penetration rate of equipped trucks. For the scenarios in which the maximum platoon size is three trucks, there are more platoons of two trucks than platoons of three trucks. It is also observed that for low penetration rates, the number of platoons is very small (2 platoons/h on average). If all trucks are equipped, this can increase to approximately 25-40 platoons/h of which approximately two out of three platoons is a platoon consisting of two trucks. Given the total numbers of heavy trucks in the simulations as shown in Table 4.1, the share of equipped trucks that is actually platooning is thus limited. This is because in this research 'on-the-fly' platoon formation in mixed traffic is used, i.e. without planning the arrival times of trucks such that they can drive in platoons, as explained in section 3.2.1. This also implies that in case of 'planned' platooning, the effects of truck platooning at motorway on-ramps will be larger.

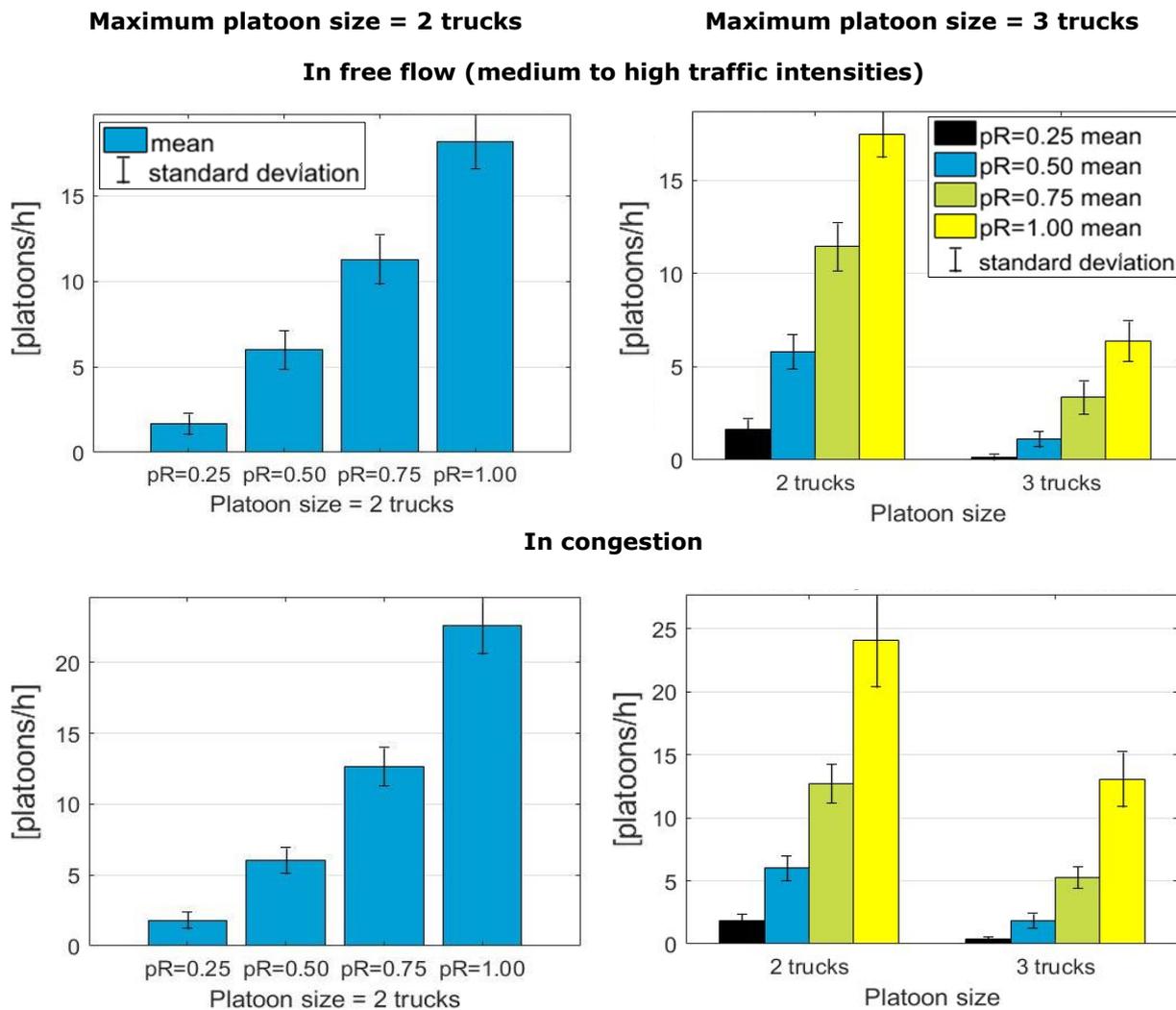


Figure 5.1: Platoon compositions in free flow for medium to high traffic intensities (top) and in congestion (bottom) for the different penetration rates (pR) of equipped trucks.

5.1.2 On-ramp merging behaviour

The effects of truck platooning on the merging behaviour of the vehicles on the on-ramp is captured by analysing the merge location distributions and the merging speed distributions as defined in section 4.3.

Merge location distributions

The merge location distributions of the platooning scenarios, aggregated for the different platoon configurations (see section 4.2.2), are displayed in Figure 5.2. The merge location distributions hardly change compared to the base scenarios. They are similar for all free flow scenarios. In free flow, most vehicles merge within 50 to 100 m after the start of the acceleration lane. Almost all vehicles have merged after 300 m. In the congestion scenarios however, most vehicles merge at between 200 and 250 m after the start of the acceleration lane. Also, many vehicles still need to merge at between 300 and 350 m. Compared to the base scenarios, the average merge location is shifted a few metres more towards the end of the acceleration lane at maximum. This is in line with the findings on behavioural adaptation from section 2.3 of the literature study. The most significant differences with the base scenarios occur at the end of the acceleration lane. As more truck platoons are present, more vehicles merge in the last 50 m of the acceleration lane. In congestion, a slightly larger share of vehicles is merging earlier than in the base scenarios, especially at higher penetration rates. The merge location distributions correspond to the findings from empirical evidence as shown in **Appendix D**, confirming the validity of the merging behaviour shown. Figure 5.2 also reveals that some vehicles are unable to merge within the length of the acceleration lane. This indicates that merging becomes more difficult in the presence of truck platoons. This problem grows with increasing penetration rate and traffic intensity.

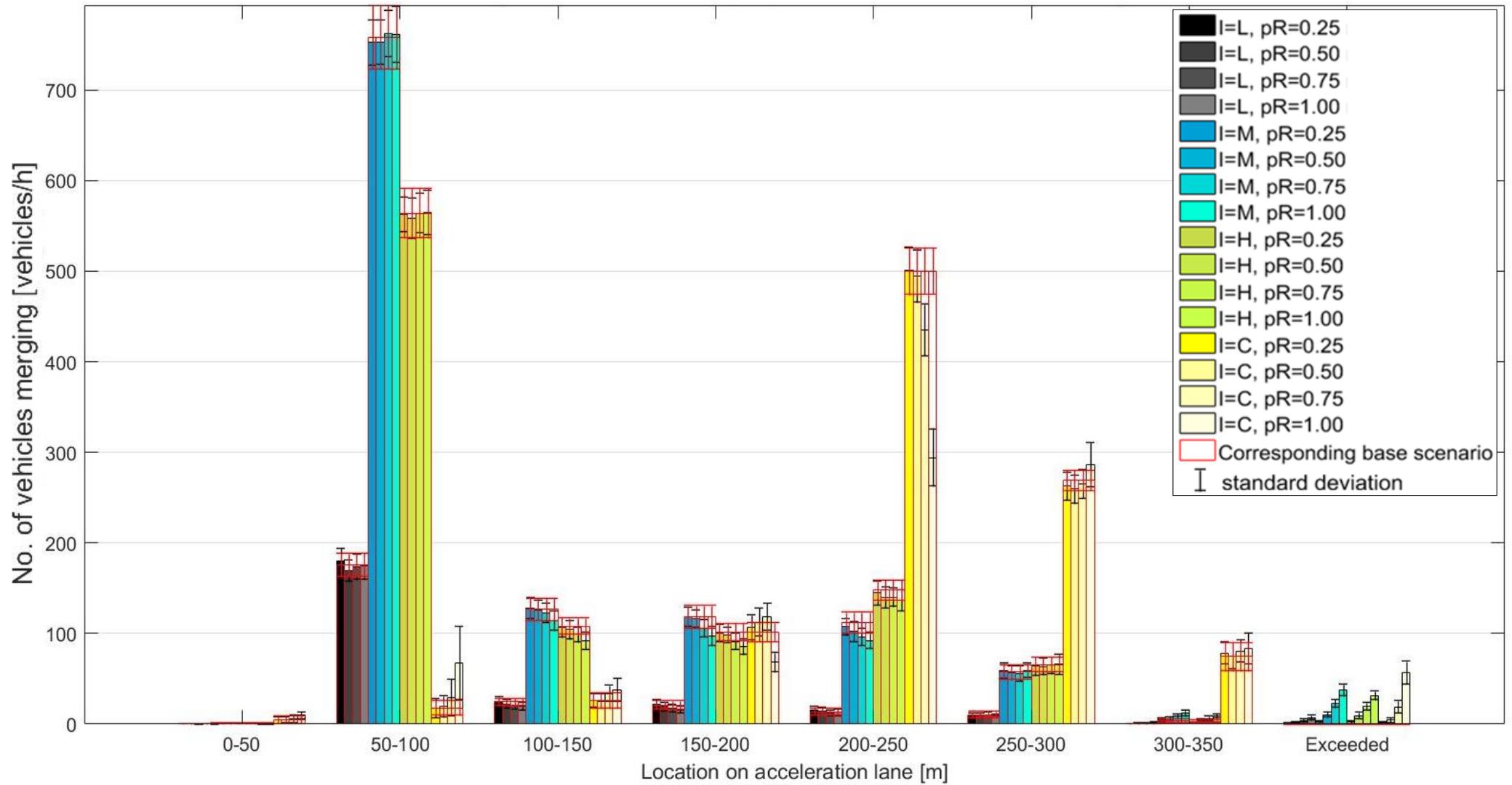


Figure 5.2: Effects of truck platooning on the average merge location distributions per penetration rate (pR) for low (L), medium (M), high (H) and congestion (C) traffic intensities (I).

The average number of vehicles per hour that are unable to merge within the length of the acceleration lane is given in Table 5.1 for the different traffic intensities and penetration rates and aggregated for the different platoon configurations (see section 4.2.2). It reveals that serious merging problems will occur only at higher penetration rates, even for a medium traffic intensity. For a penetration rate of 25% or lower, hardly any vehicles are unable to merge in time. The fact that inability to merge occurs more often for the medium traffic intensity than for the high traffic intensity reveals that the intensity on the on-ramp is more determining for merging issues than the intensity on the motorway itself.

Table 5.1: Effects of truck platooning on the ability of vehicles to merge at the on-ramp.

Penetration rate	0%	25%	50%	75%	100%
Traffic intensity	Average number and share of vehicles unable to merge per hour				
Low	0	0.5 (0.2%)	1.8 (0.75%)	4.1 (1.7%)	7.1 (3.0%)
Medium	0	2.4 (0.2%)	10.6 (0.9%)	22.9 (2.0%)	37.5 (3.2%)
High	0	2.3 (0.2%)	9.4 (1.0%)	19.8 (2.0%)	31.8 (3.2%)
Congestion	0	1.1 (0.1%)	4.6 (0.5%)	19.1 (1.9%)	56.8 (5.7%)

The numbers and shares of vehicles unable to merge are also given in Figure 5.3 and Figure 5.4 respectively. Apart from the average numbers and shares (displayed as continuous lines), the highest and lowest observed values are also given (displayed as dashed lines). This results in upper and lower bounds between which the number or share of vehicles unable to merge lie, depending on the maximum platoon size and CACC time gap applied. These differences between the maximum platoon size and CACC time gap will be addressed in the next paragraph. It can clearly be seen that the number of vehicles unable to merge increases rapidly with increasing penetration rate. In free flow, the share of merging vehicles that are unable to merge is more or less independent of the traffic intensity. In congestion, the share of vehicles unable to merge only becomes larger than in free flow above a penetration rate of 75%. Even at 100% penetration rate, the share of vehicles unable to merge is never larger than approximately 9%.

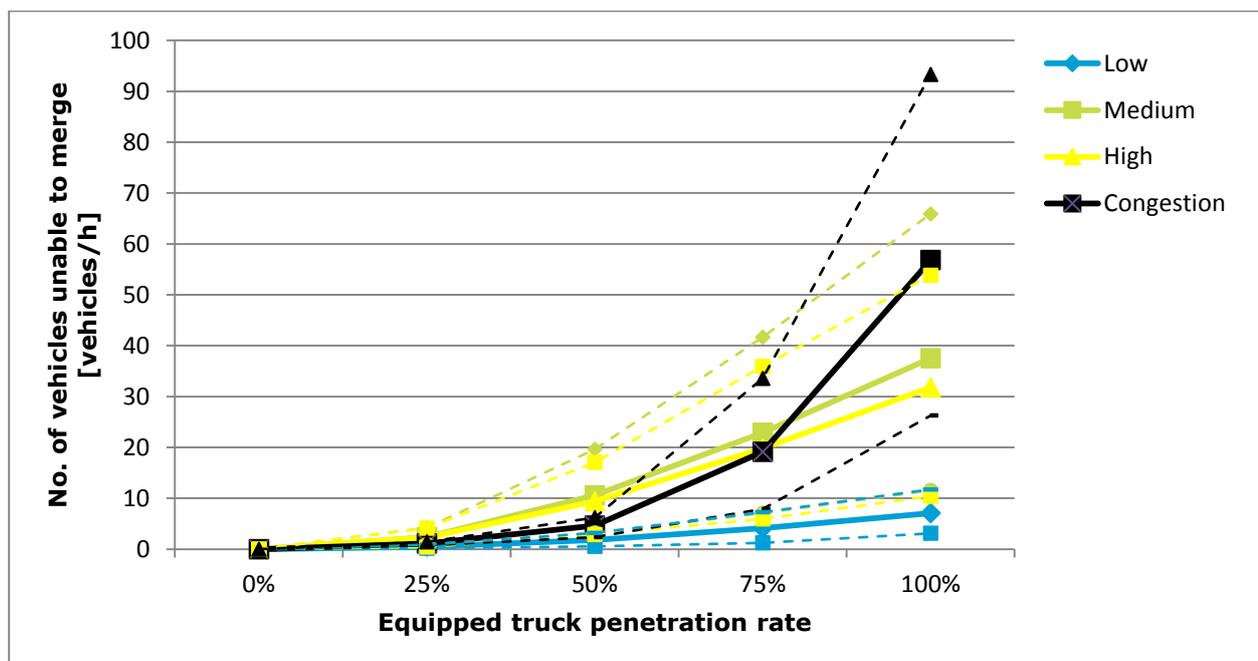


Figure 5.3: Number of vehicles unable to merge per traffic intensity. The averages are displayed as continuous lines and the highest and lowest observed values as dashed lines.

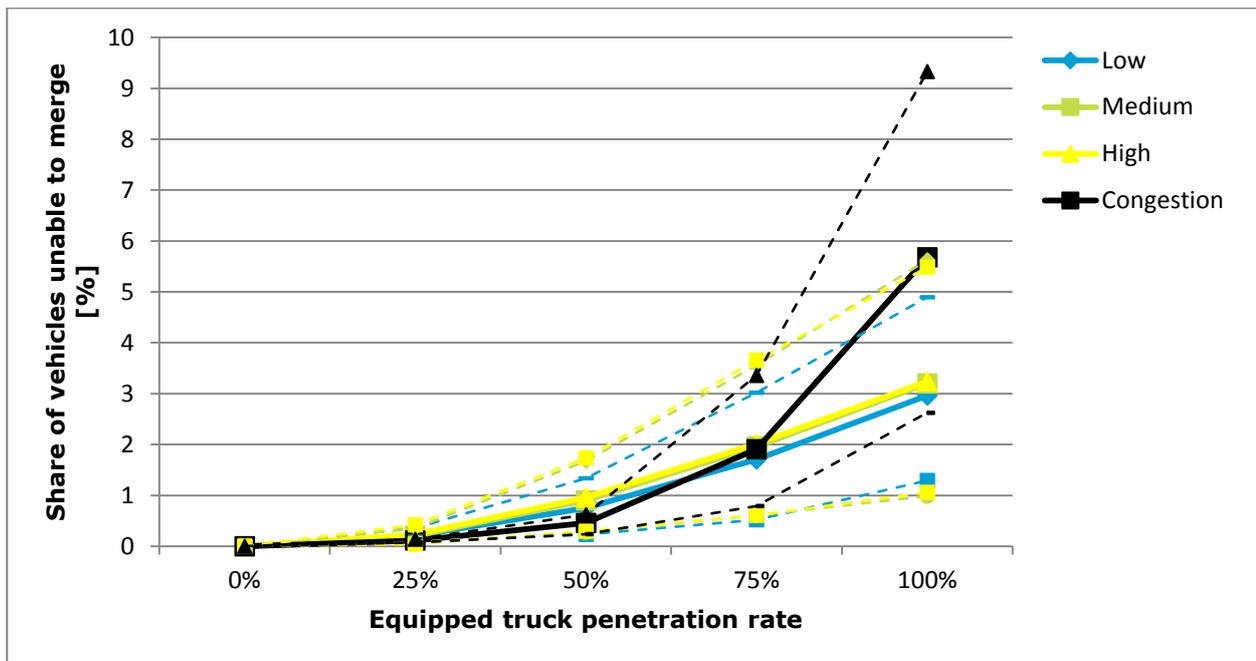


Figure 5.4 Share of merging vehicles unable to merge per traffic intensity. The averages are displayed as continuous lines and the highest and lowest observed values as dashed lines.

Merging speed distributions

The speeds at which vehicles merge hardly change due to truck platooning as shown in Figure 5.6 for the different traffic intensities and penetration rates. Similar to the base scenarios, they increase along the acceleration lane from approximately 75 up till 100 km/h during free flow. Thereby the difference between the scenarios and the standard deviation increases somewhat, whereby the merging speeds in free flow are highest for the low traffic intensity and lowest for the high traffic intensity. For the free flow scenarios, the average merging speed is between 80 and 90 km/h on average. In free flow, significant differences with the base scenarios only occur in the last 50 m of the acceleration lane. The merging speeds drop on average from 100 km/h to approximately 90 km/h. Starting from medium traffic intensity, this drop is larger for higher penetration rates. This is in line with the empirical findings from section 2.3 of the literature study. The penetration rate of equipped trucks hardly has an effect on the merging speeds in free flow.

The congestion scenarios do not show large differences with the base scenarios either. Obviously merging speeds are much lower than in free flow, with lowest average speeds of between 10 and 20 km/h observed in approximately the middle of the acceleration lane (100-250 m). In congestion, the merging speeds show a large variability as reflected by the high standard deviations. At the beginning and the end, average merging speeds are a little higher (between 25-50 km/h). The relatively low speeds in congestion between roughly 150 and 250 m after the start of the acceleration lane can be explained by the fact that this is where the queue is formed, as illustrated by a simulation screenshot in Figure 5.5. Vehicles display this behaviour because they are near the end of the acceleration lane and thus start synchronizing with the traffic on the motorway.

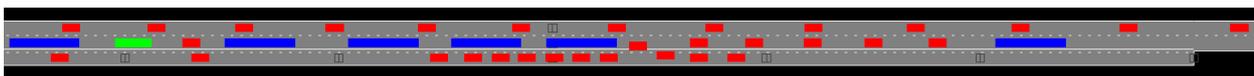


Figure 5.5: Queue formation on the acceleration lane during congestion.

The penetration rate only has a significant effect on the merging speeds when it is higher than 50% as shown in Figure 5.7. The average merging speed can increase from 17 km/h to approximately 30 km/h when all trucks are equipped.

As illustrated in the previous section by Figure 5.3, the number of vehicles unable to merge in time increases with increasing penetration rate. Since these vehicles are deleted from the simulations, they are not included in the calculation of the average merging speeds. In reality these vehicles would still have to merge by either stopping at the end of the acceleration lane and waiting for a suitable gap or

by continuing on the shoulder lane, as was also described in section 2.3 of the literature study. Therefore, the increase in average merging speeds as observed in the simulations is likely to be smaller in reality. The amount of increase that is left if no vehicles are deleted is addressed in section 5.2.

Differences in merging behaviour between the platoon configurations

The effects of truck platooning on the merging behaviour is different for the maximum platoon sizes and the CACC time gaps considered.

A maximum platoon size of three trucks increases merging problems compared to a maximum platoon size of two trucks as illustrated in Figure 5.7. This is because a platoon of three trucks is longer than a platoon of two trucks and hence forms a longer barrier for merging vehicles. The number of vehicles unable to merge in time increases with higher on-ramp traffic intensities and penetration rates. The number of vehicles unable to merge in time can be almost 1.5 times as high in free flow and twice as high in congestion for a maximum platoon size of three trucks at high intensities and penetration rates. The rest of the merge location distribution is hardly different for the two maximum platoon sizes.

In free flow, the average merging speed is hardly different for the two maximum platoon sizes. In case of congestion, the average merging speed is on average approximately 10 to 30 % higher for a maximum platoon size of three trucks, increasing with increasing penetration rate as shown in Figure 5.7. Below a penetration rate of 50% there are however no differences between the maximum platoon sizes. As explained in the previous paragraph, the differences may be (partially) caused by the differences in the number of deleted vehicles. Apart from the differences in average merging speeds, the rest of the merging speed distribution is hardly different for the two different maximum platoon sizes.

Smaller CACC time gaps reduce the number of vehicles unable to merge in time as shown in Figure 5.7. This is because a platoon with a larger time gap is longer than a similar platoon with a smaller time gap and hence forms a longer barrier for merging vehicles. The decrease in the number of vehicles unable to merge in time is larger for higher traffic intensities and penetration rates. Thereby the effect is largest for medium and high traffic intensities. The number of vehicles unable to merge in time can be more than three times as high in free flow and almost twice as high in congestion for a CACC time gap of 0.7 s compared to a CACC time gap of 0.3 s at high penetration rates. Similar to the two maximum platoon sizes, the rest of the merge location distribution is hardly different for the three CACC time gaps.

Similar to the two different maximum platoon sizes, the CACC time gap setting hardly influences the average merging speeds of vehicles in free flow as shown in Figure 5.7. In case of congestion, the average merging speed is also hardly different for the different time gaps. Interestingly, for penetration rates above 50 to 75%, the increase in average merging speed is slightly larger for a time gap of 0.7 s than for the smaller time gaps. This can again be declared by the fact that the merging speed of deleted vehicles is not taken into account.

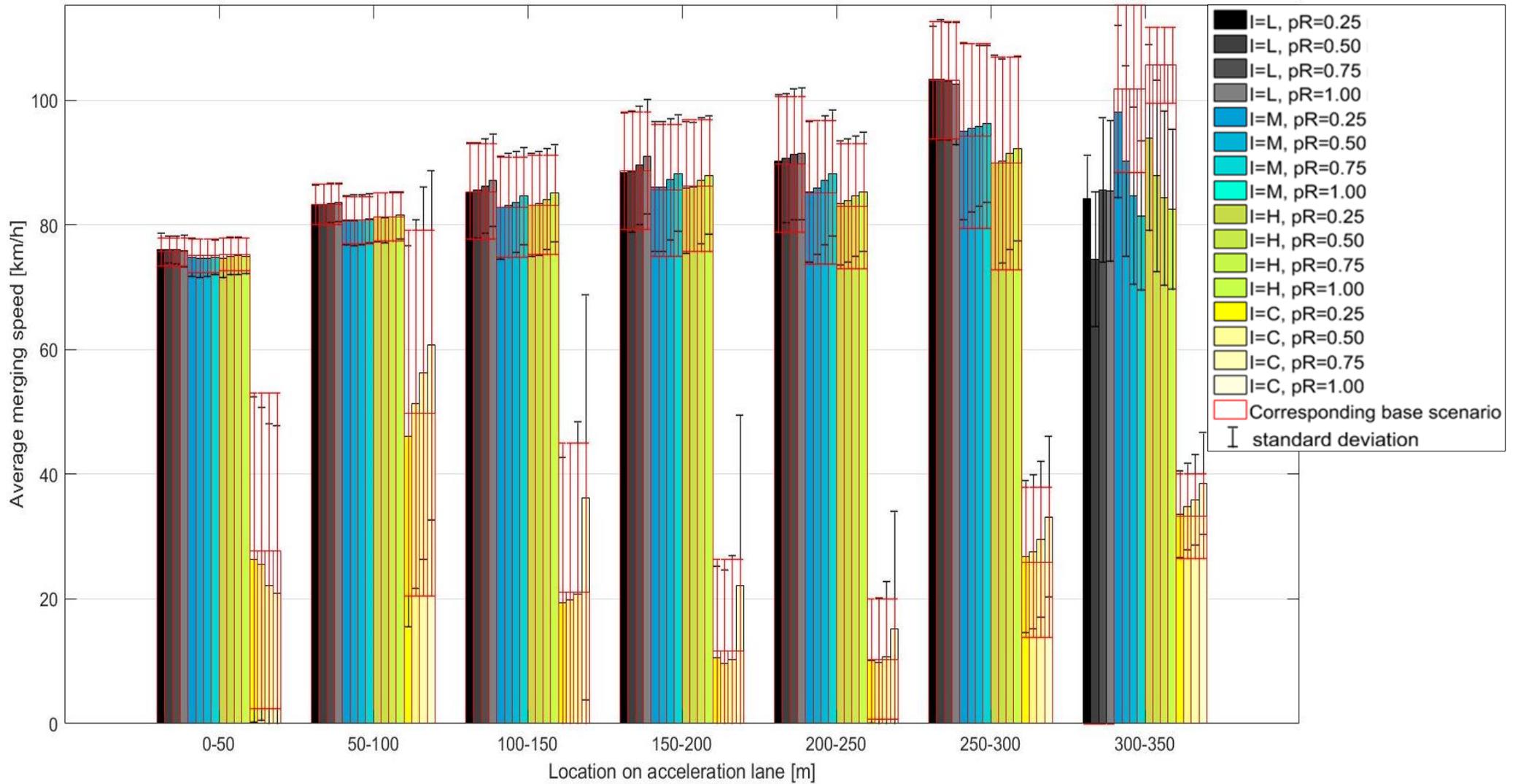


Figure 5.6: Effects of truck platooning on the average merging speed distributions per penetration rate (pR) for low (L), medium (M), high (H) and congestion (C) traffic intensities (I).

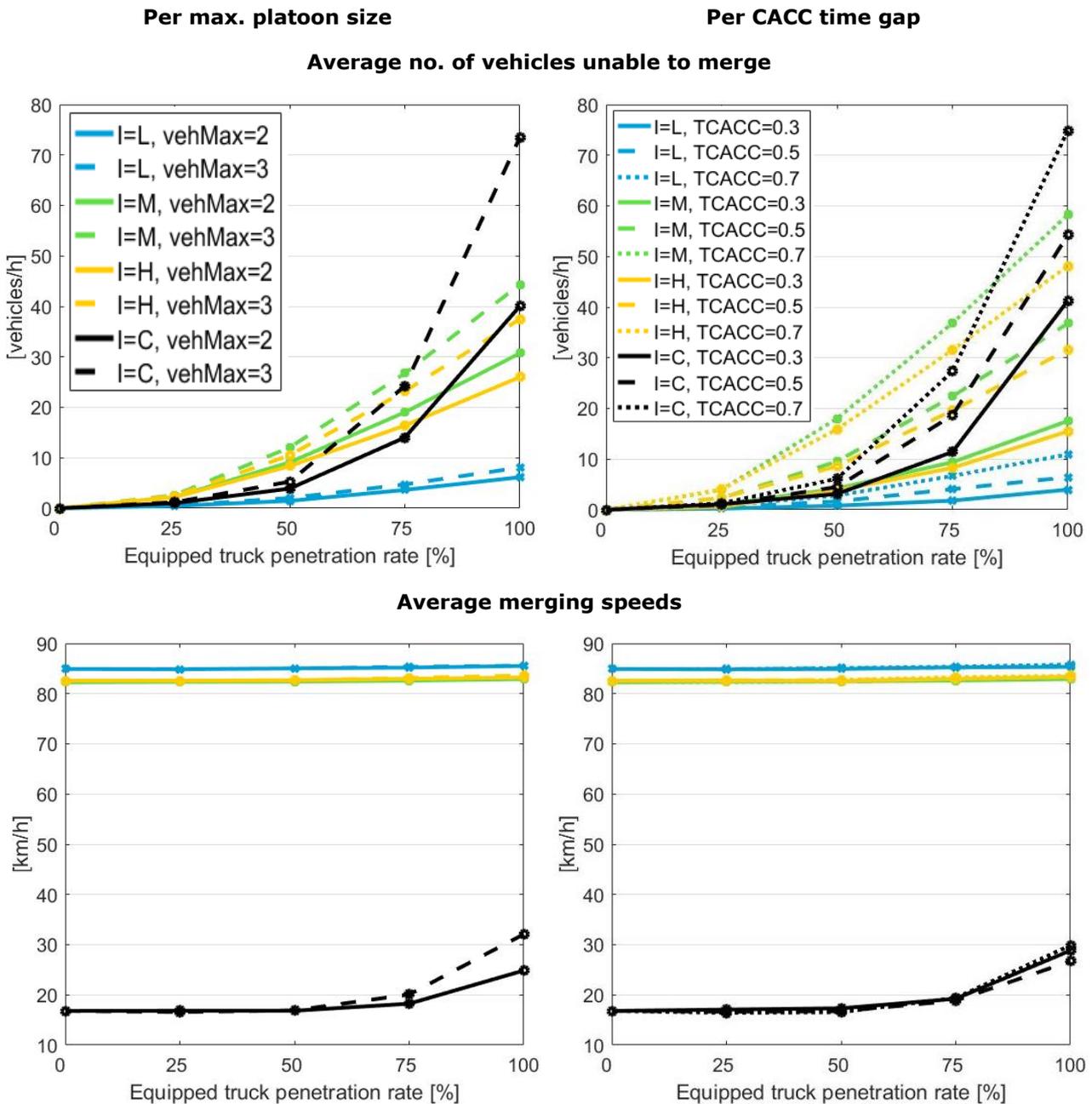


Figure 5.7: Effects of truck platooning on ability to merge and average merging speeds per maximum platoon size (vehMax) and CACC time gap (TCACC).

5.1.3 Motorway traffic safety and performance

The effects of truck platooning at the on-ramp on the performance of traffic and safety on the motorway is captured by analysing inter-vehicle gap distributions, the corresponding time-to-collision (TTC) distributions including the time-exposed and time-integrated time-to-collision, as well as network level indicators total time spent, maximum outflow and average speed difference between the left and the right lane. The resulting traffic states on the motorway are then captured in fundamental diagrams and flow- and speed-contour plots. An explanation of these performance indicators can be found in section 4.3.

Gap distributions

The inter-vehicle gaps maintained by the human drivers hardly changes due to truck platooning. Similar to the base scenarios, average time gaps are higher upstream of the acceleration lane than downstream of the acceleration lane, which can be declared by increasing density downstream because of the inflow of vehicles at the on-ramp. The smallest time gaps observed occur at the on-

ramp area, caused by merging vehicles and relaxation behaviour. A very minor reduction in the average gap maintained at the on-ramp area is observed compared to the base scenarios. This is likely caused by the behavioural adaptation that was implemented for merging vehicles based on section 2.3 of the literature study, accepting smaller gaps when interacting with truck platoons (see section 3.2.2).

Time-to-collision distributions

Truck platooning does not lead to extra unsafety in terms of severity and frequency of occurrence of unacceptable time-to-collision (TTC) values. The TTC distributions in free flow are very similar to the base scenarios. In free flow, hardly any cases with TTCs below 10 s are observed, although the number of observations of TTC values below 10 s increases with increasing traffic intensity. In congestion, the TTC distributions are very different from the ones that apply in free flow. The peak in the observations lies at 3.5 s and a significant amount of observations as low as 1.4 s occur. Thereby any values below 3 s can be regarded as dangerous (see section 4.3.2). The low values can be explained by merging manoeuvres and shockwaves in the jam. Similar to the gap distributions, the smallest TTCs occur at the on-ramp area.

Similar to the base scenarios, time-exposed (TE) and time-integrated (TI) TTCs among the conventional vehicles are zero during free flow. This means that there are no occasions at which vehicles are at high risk of colliding with their predecessor. In congestion, there is a large reduction of the TE- and TI-TTCs with up to 92% for the on-ramp area and even 100% in the queue upstream of the on-ramp area. This reduction increases approximately linearly with increasing penetration rate. The resulting TE- and TI-TTCs are displayed in Figure 5.8 for the entire network. It must be noted though that the large reduction in TE- and TI-TTCs compared to the base scenario in case of congestion is partly caused by the fact that the equipped trucks are excluded from the TTC distributions (see section 4.3.2), so that the TE- and TI-TTCs are calculated for fewer vehicles as the penetration rate increases. However, this can only explain a difference of 20% at maximum. The reduction in TE- and TI-TTCs thus still remains very large.

Finally, when analysing TTC values, one has to keep in mind that very small inter-vehicle gaps are not considered unsafe if the speed difference between the vehicles in question is very small. The analysis of the gap distributions in the previous paragraph however revealed that such dangerously small gaps are not present in the platooning scenarios.

Differences between the platoon configurations

There is no difference in TTC distributions and the TE- and TI-TTCs between the maximum platoon sizes of two or three trucks as shown in Figure 5.8. However, this is not true for the different CACC time gaps. The TE-TTC and TI-TTCs are lower for larger time gaps, implying that larger CACC time gaps are safer for the conventional vehicles. For a time gap of 0.3 s, the values can be approximately twice as high as for a time gap of 0.7 s. Interestingly, this difference is highest for penetration rates between 50 and 75% and almost non-existent for very low or very high penetration rates.

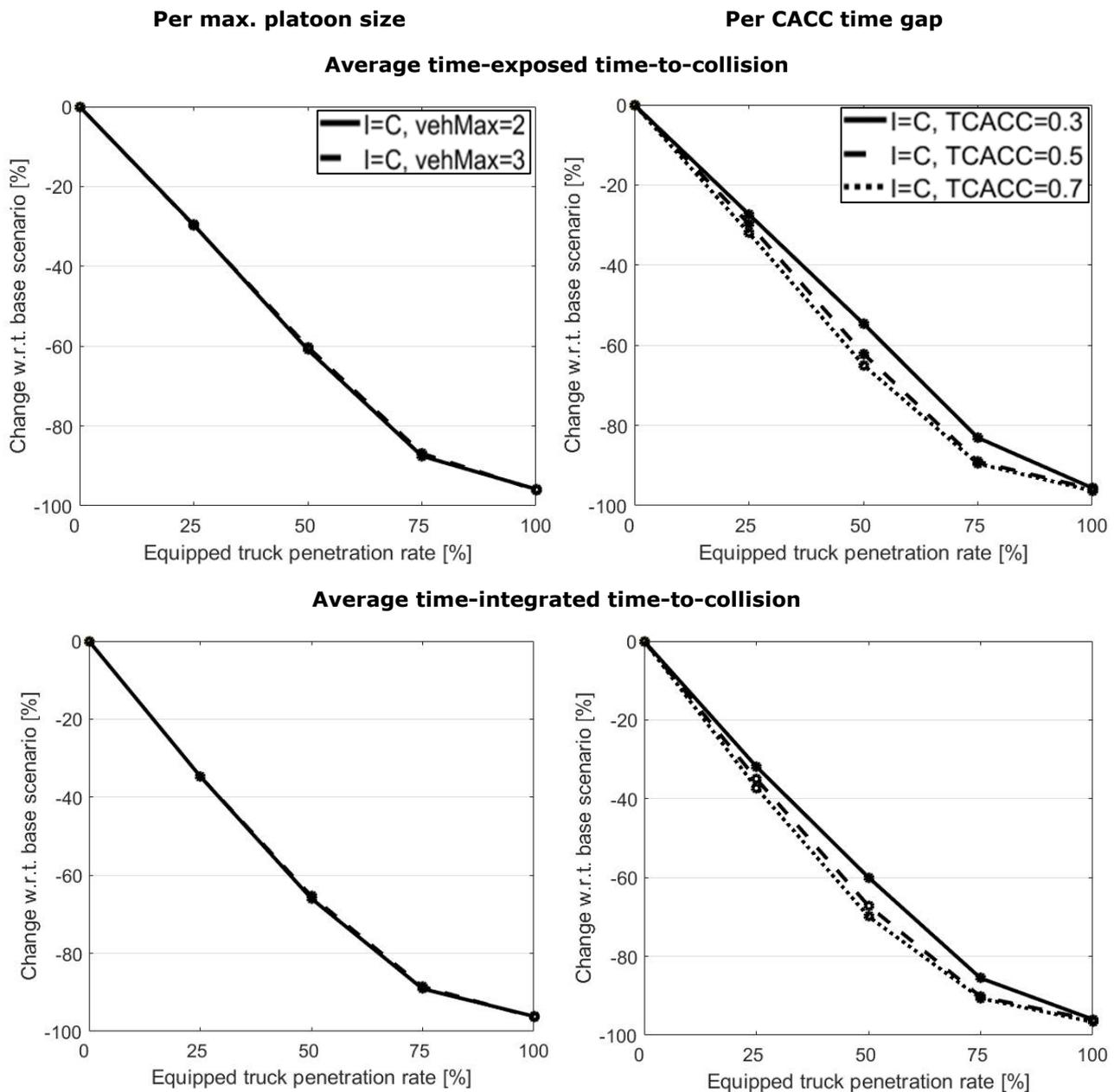


Figure 5.8: Effects of truck platooning on TE- and TI-TTCs per maximum platoon size (vehMax) and CACC time gap (TCACC).

Total time spent (TTS)

In free flow, the effects of truck platooning on the TTS are small. The TTS in free flow decreases slightly with increasing penetration rate, but the maximum decrease is less than 2% when all trucks are equipped as shown in Figure 5.10. Thereby the decrease is largest for scenarios with the highest on-ramp intensity. During congestion, the decrease in TTS is much larger. It decreases with increasing penetration rate up to approximately 16% on average when all trucks are equipped. As explained in the previous section, the reduction may be (partially) caused by the fact that some vehicles are deleted and thus no longer spent time in the network. The amount of decrease that is left if no vehicles are deleted is addressed in section 5.2.

Maximum outflow

The maximum outflow confirms the pattern found for the TTS. During free flow the effect of truck platooning on maximum outflow is negligible, but during congestion a significant effect on maximum outflow is found to exist. In the congestion scenarios, the maximum outflow gives an indication of capacity, since it is observed just before congestion starts forming (Henkens and Tamminga 2015). It

is found that capacity increases linearly with increasing penetration rate. At 25% penetration rate the capacity increase is limited to approximately 2% on average, but it increases with up to 19% (to 4563 vehicles/h) when all trucks are equipped as shown in Figure 5.9. This is a major capacity increase, illustrating one of the positive potential effects of truck platooning on traffic flow. However, once again, the increase may be (partially) caused by the fact that some vehicles are deleted and do not merge, so that the traffic flow on the motorway is disrupted less than if these vehicles would have merged. The amount of increase that is left if no vehicles are deleted is addressed in section 5.2.

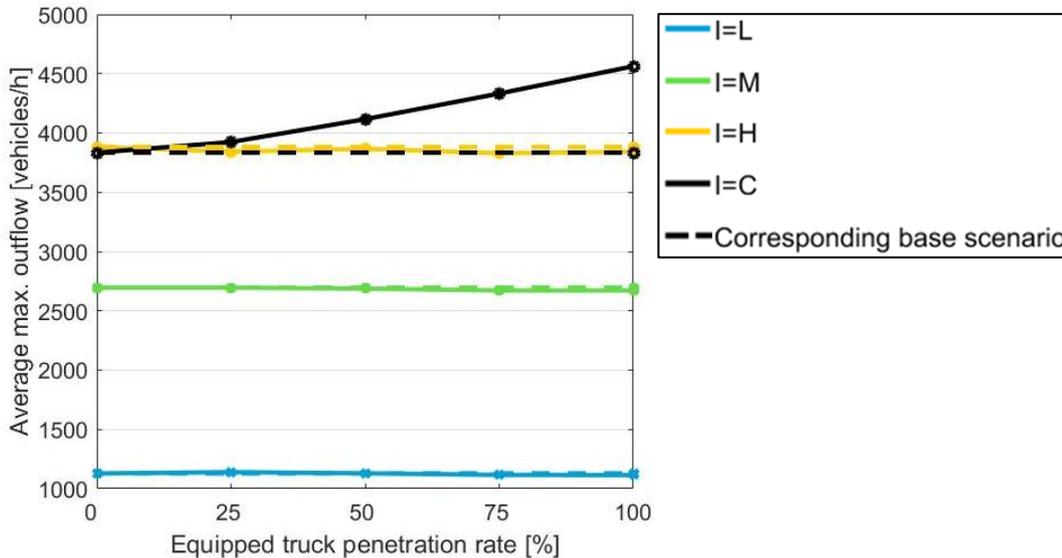


Figure 5.9: Effects of truck platooning on maximum outflow.

Average speed difference between the left and the right lane

The inhomogeneity of traffic states across the lanes, measured by the average speed difference between the left and the right lane as shown in Figure 5.10 hardly changes in free flow due to truck platooning. It decreases slightly with increasing penetration rate up to approximately 3% if all trucks are equipped. This reduction is slightly larger for lower traffic intensities. During congestion however, a huge increase in speed difference compared to the base scenario is observed. This is caused by the fact that especially traffic flow in the left lane does not break down as much as in the right lane. This on its turn might be caused by the fact that truck platoons are not allowed to change lanes.

Differences between the platoon configurations

In free flow there is little to no difference in traffic performance between the two maximum platoon sizes. In congestion and depending on the penetration rate, the TTS can be up to approximately 8% smaller and the maximum outflow up to approximately 3% higher for a maximum platoon size of three trucks compared to two trucks. This effect grows with increasing penetration rate as shown in Figure 5.10. The average speed difference between the left and the right lane is approximately 5% higher for a maximum platoon size of three trucks compared to two trucks.

Similarly, there is no clear difference in traffic performance between the three CACC time gaps in free flow as also shown in Figure 5.10. During congestion however, the TTS can be up to approximately 3% smaller and the maximum outflow up to approximately 2% higher for the smallest CACC time gap of 0.3 s compared to the largest CACC time gap of 0.7 s. However, at penetration rates above approximately 85%, the TTS reduction becomes larger for the largest time gap of 0.7 s. This might be because more vehicles are deleted with this time gap, so that they no longer spend time in the network. The time gap setting does not seem to affect the average speed difference between the left and the right lane, since there is no structural difference for the different time gap settings.

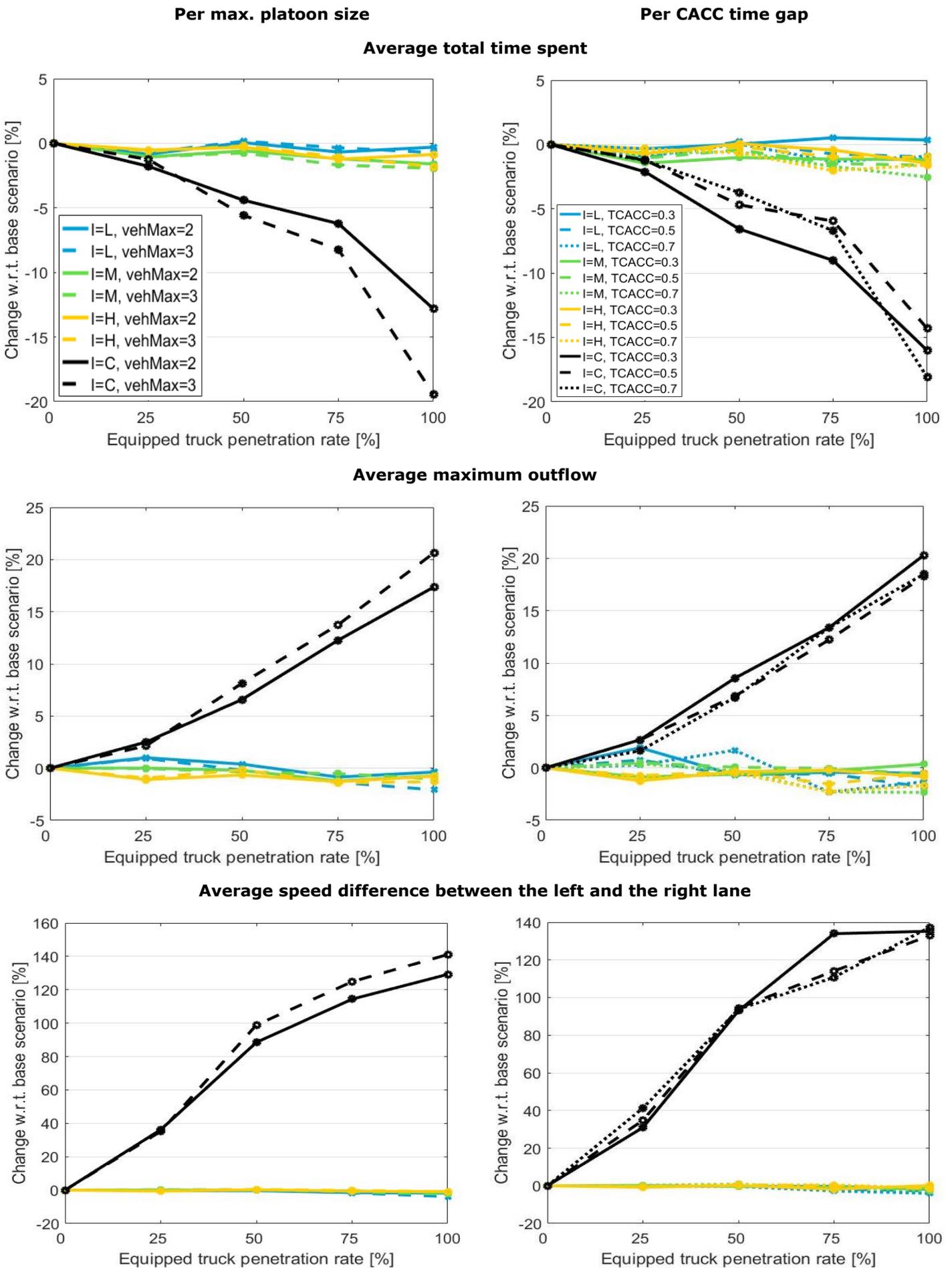


Figure 5.10: Effects of truck platooning on TTS, max. outflow and average speed difference between left and right lane.

Flow- and speed-contour plots and fundamental diagrams

Analysis of the flow- and speed-contour plots and fundamental diagrams reveals that no significant differences in traffic states occur due to truck platooning in free flow. The average speeds observed are slightly higher in case of truck platooning (approximately 2 km/h). At medium to high intensities, the maximum flows observed are slightly lower for the left lane (max. 3%), but often slightly higher for the right lane (also max. 3%). In congestion the differences with the base scenario are much larger as shown in the fundamental diagrams of Figure 5.12. The congestion becomes less severe due to truck platooning. Maximum flows observed for the left lane do not differ much, but the maximum flows in the right lane increase significantly at higher penetration rates (up to 21% at 100% penetration rate). The breakdown of traffic in both lanes becomes less severe. High flows are maintained at higher densities (from 20 to max. 30 vehicles/km) and the average and minimum flows (from 432 to max. 672 vehicles/h) and speeds (from 10 to 15 km/h) observed are higher. In congestion and at high penetration rates, truck platooning also has the effect that it takes much longer for the jam to form as shown in the speed-contour plots of Figure 5.11. Whereas the jam is present from the first minute of simulation in the congestion base scenario, it may take up to 15 minutes before the jam with speeds below 50 km/h starts forming in a platooning scenario in which all trucks are equipped.

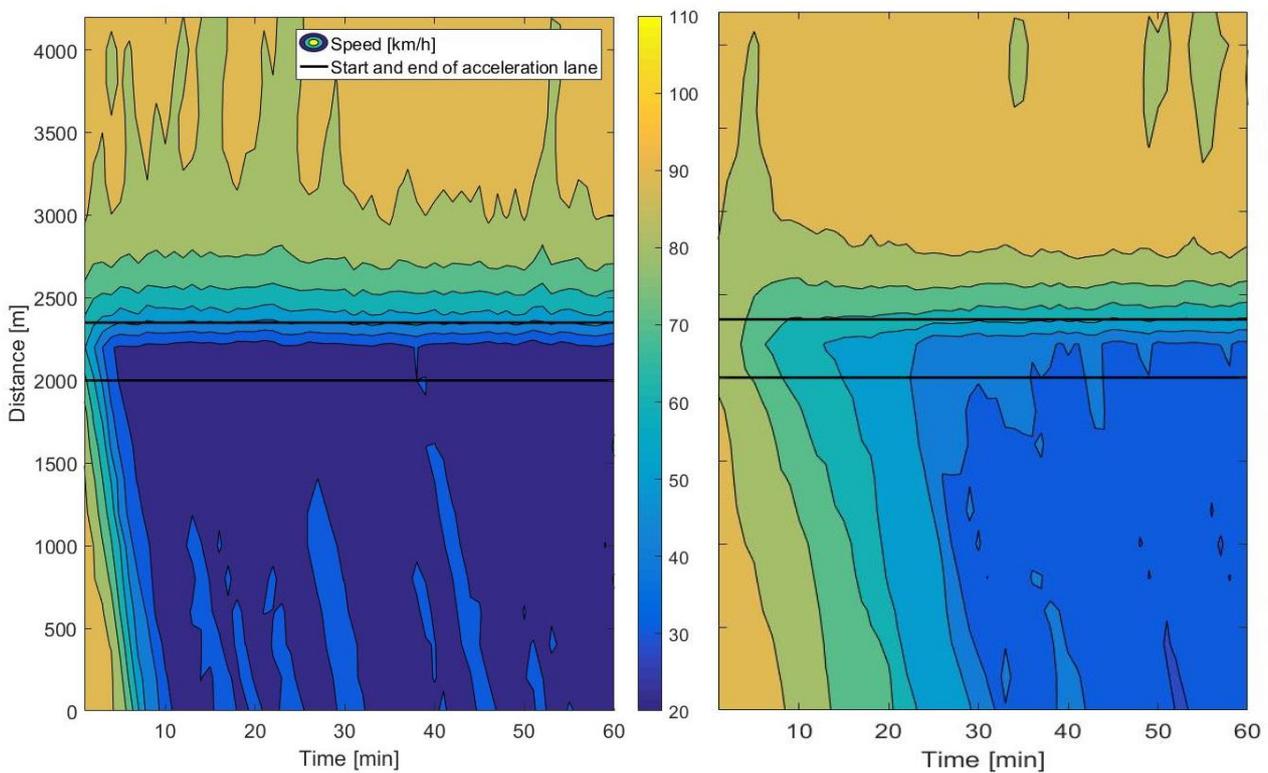


Figure 5.11: Effects of truck platooning on the onset of and speeds in congestion: congestion base scenario (left) vs. platooning scenario (100% pen. rate).

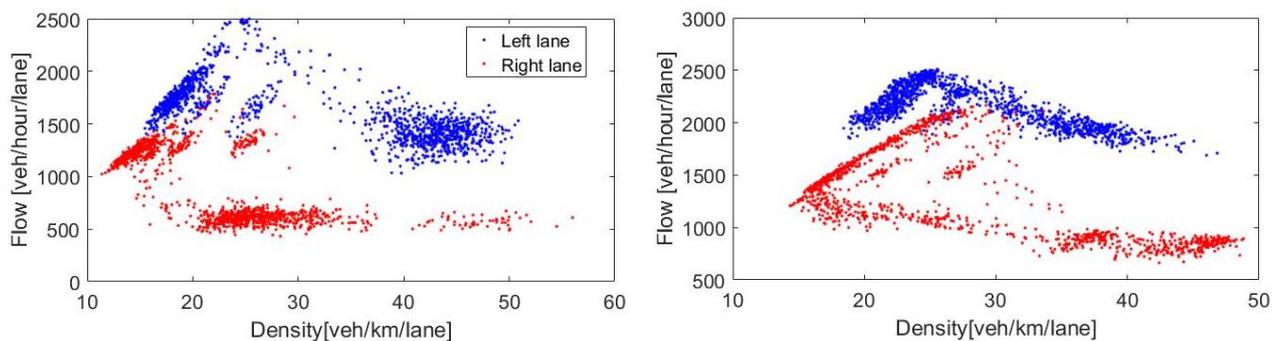


Figure 5.12: Effects of truck platooning on the fundamental diagrams: congestion base scenario (left) vs. platooning scenario (100% pen. rate).

5.1.4 Conclusions on truck platooning effects

The simulation results show that truck platooning at on-ramps make merging more difficult and many vehicles may be unable to merge in time. In the simulations, the vehicles that cannot merge in time are simply deleted, but in reality these vehicles would of course still have to merge. This means that the positive effects that were found for the traffic performance, i.e. the reduced total time spent by all vehicles, the increased maximum outflow and the slower onset of and increased speeds in congestion could be smaller in reality. Therefore, the other platooning strategies 'allow yielding' and 'allow lane changing' and the CACC time gap larger than the minimum accepted gap will be researched in the next section to find out whether these can solve the merging problems and what the effects are on the motorway traffic performance and safety.

5.2 Analysis of possible solutions to merging problems

The previous section revealed that a significant number of vehicles have difficulty merging in time at the on-ramp. This problem gets larger as more truck platoons are passing the on-ramp. However, the results in the previous section addressed the 'fixed gap' platooning strategy. Truck platoons never yielded for merging vehicles to create a gap nor did they perform courtesy lane changes (see section 4.2.1 for an explanation of the strategies). Therefore, in this section, the effects of truck platooning if this yielding or lane changing is allowed is discussed in sections 5.2.1 and 5.2.2 respectively. This reveals whether any of these two other strategies can solve, or at least decrease the severity of these merging problems. Thereby most attention is paid to the 'allow yielding' strategy since it is by far most effective in solving merging problems. Moreover, the previous section also only addressed CACC time gaps that are smaller than the minimum gap that is accepted by lane-changing vehicles. A CACC time gap larger than this minimum might enable more vehicles to merge as well, possibly also decreasing the severity of the merging problems. The effects of this CACC time gap of 0.9 s (see section 4.2.2) are briefly discussed as well in section 5.2.3.

5.2.1 Effects of allowing yielding

In this section, the effects of allowing truck platoons to yield for merging vehicles are compared to the effects found for the 'fixed gaps' strategy explained in the previous section.

On-ramp merging behaviour

The simulation results reveal that allowing truck platoons to yield for merging vehicles effectively **solves merging problems**. Merging vehicles are no longer unable to merge in time. Instead, those vehicles now merge within the last 100 m of acceleration lane. This is reflected in the average merge location: it shifts a few metres further towards the end of the acceleration lane as shown in Figure 5.13. Apart from the latter, the merge location distribution looks the same as with the 'fixed gaps' strategy.

The fact that all vehicles can now merge has the result that the average merging speed in congestion increases much less with increasing penetration rate than with the 'fixed gaps' strategy as shown in Figure 5.13. The average merging speed is now only different from the base scenarios if more than 75% of the trucks are equipped and increases with only 3 km/h on average when all trucks are equipped. Apart from the end of the acceleration lane, the merging speed distribution does not change. Allowing yielding also has the effect that the differences in merge location and merging speed distributions between the maximum platoon sizes and the CACC time gaps are reduced and become almost zero.

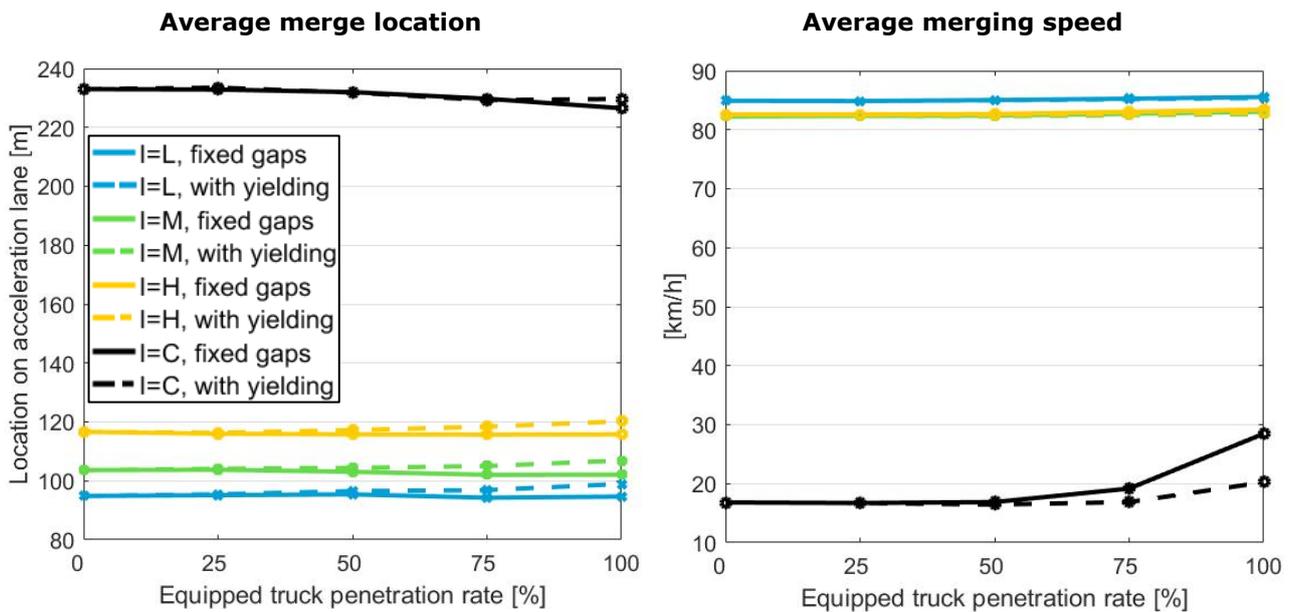


Figure 5.13: Effects of allowing yielding on merging behaviour.

Motorway traffic safety and performance

The severity and frequency of occurrence of conflicts expressed as the time-exposed and time-integrated time-to-collision are not affected when yielding is allowed. Unsafe situations still only occur in congestion. For the equipped trucks, the number of observations of critical TTC values in congestion increases marginally, caused by the fact that more vehicles merge in front of equipped trucks at small gaps. The average time gap maintained by human drivers in congestion increases very little (max. 0.06 s) and the number of observations of time gaps below 1 s decreases marginally. However, the total effect on safety in terms of TE- and TI-TTC is negligible as shown in Figure 5.14. It is concluded that it becomes a little safer for the conventional vehicles since they can always merge and slightly fewer small time gaps occur and a little more unsafe for the truck platoons since they are confronted with vehicles cutting in at small gaps, but the differences are very small. Allowing yielding does not change the differences in TE- and TI-TTCs between the different maximum platoon sizes and CACC time gaps.

If platoons are allowed to yield for other vehicles, the effects of truck platooning on traffic flow become smaller than with the 'fixed gaps' strategy. The total time spent in the network by all vehicles is still reduced compared to the base scenarios, but less than with the 'fixed gaps' strategy as shown in Figure 5.14. The maximum TTS reduction in congestion is now 9% (was 16%) and the maximum increase in maximum outflow 15% (was 19%), corresponding to 4395 vehicles/h. This shows that even when no vehicles are deleted because they could not merge in time, there is still a potential capacity increase when truck platooning is introduced. The speed difference between the left and the right lane is hardly different compared to the 'fixed gaps' strategy as shown in Figure 5.14. During congestion, however, the speed difference is very slightly larger, caused by the fact that the speeds in the right lane become slightly lower as the truck platoons yield for merging vehicles.

Although allowing yielding has no effect on the differences between the maximum platoon sizes, the differences between the CACC time gaps increase a little. The TTS can now be up to approximately 5% (was 3%) smaller and the maximum outflow up to approximately 4% (was 2%) higher for the smallest CACC time gap of 0.3 s compared to the largest gap of 0.7 s. This could be caused by the fact that a truck platoon driving at small CACC gaps takes longer to create a suitable gap for merging vehicles when yielding than a platoon with larger gaps. The speed difference between the lanes is not affected.

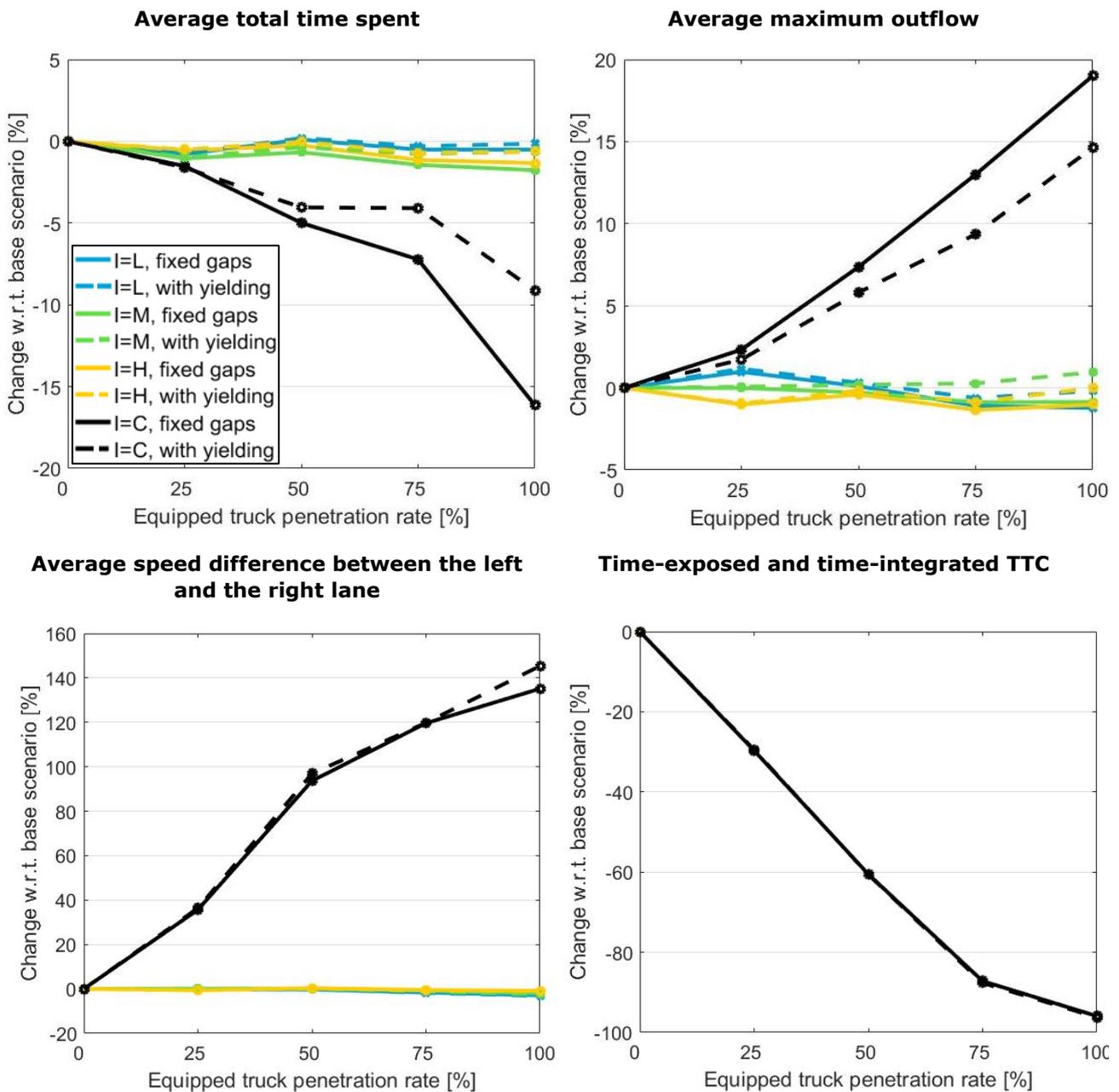


Figure 5.14: Effects of allowing yielding on TTS, max. outflow, average speed difference left vs. right lane and TE- and TI-TTCs.

The flow- and speed-contour plots only differ from the 'fixed gaps' strategy in case of congestion. The onset of congestion is faster and the breakdown of traffic more severe, thereby shifting more towards the base scenario as shown in Figure 5.15. This is caused by the fact that, similar to the base scenarios, all vehicles are now able to merge and all vehicles, including the truck platoons, are able to yield for merging vehicles. Allowing yielding thus has the effect that the impact of truck platooning on traffic flow becomes smaller than with the 'fixed gaps' strategy. However, the onset of congestion is still slower and the speeds in the jam are still higher than in the base scenario as can be seen when comparing Figure 5.15 to Figure 5.11. This difference is larger with increasing penetration rate. The fundamental diagrams confirm the differences between the 'fixed gaps' and 'allow yielding' strategies observed in the flow- and speed-contour plots: the minimum flows observed in the right lane are lower and the maximum density is higher as shown in Figure 5.16.

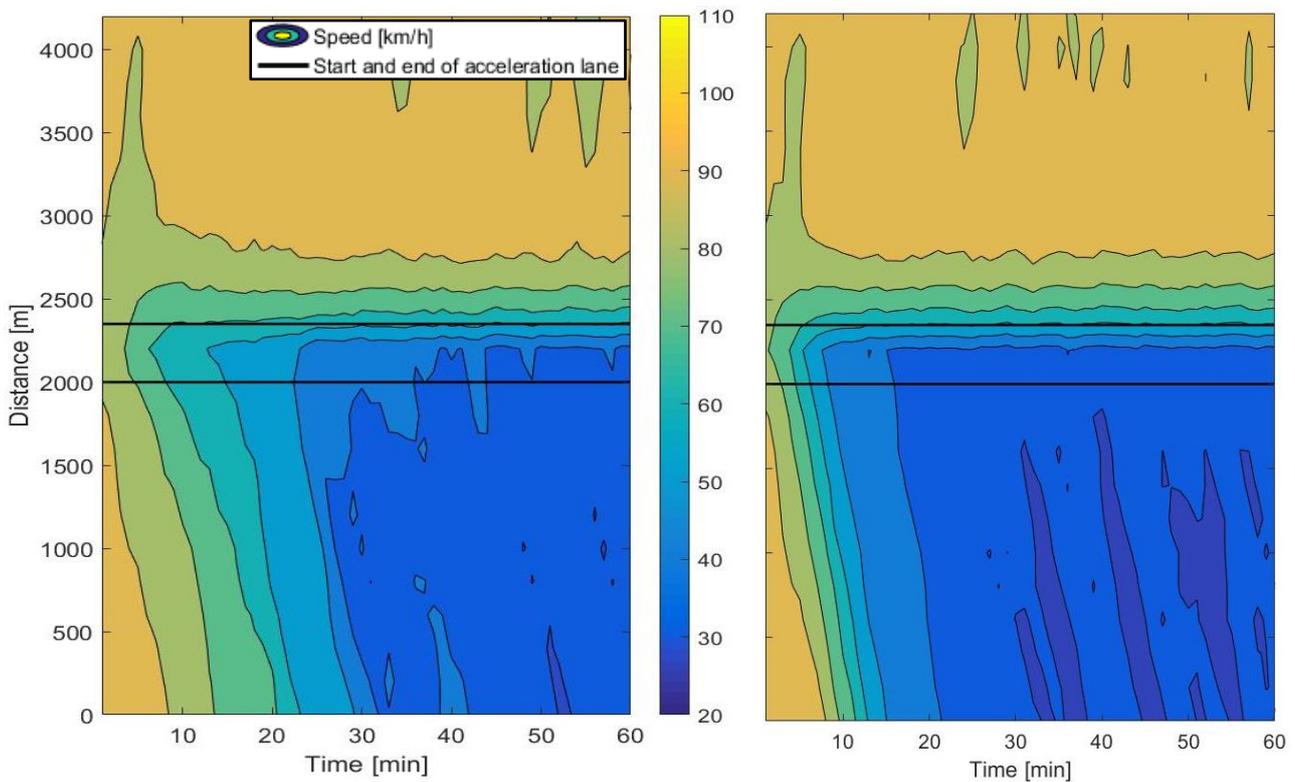


Figure 5.15: Effects of allowing yielding on the onset of and speeds in congestion: 'fixed gaps' strategy (left) vs. 'allow yielding' strategy (right) (100% pen. rate).

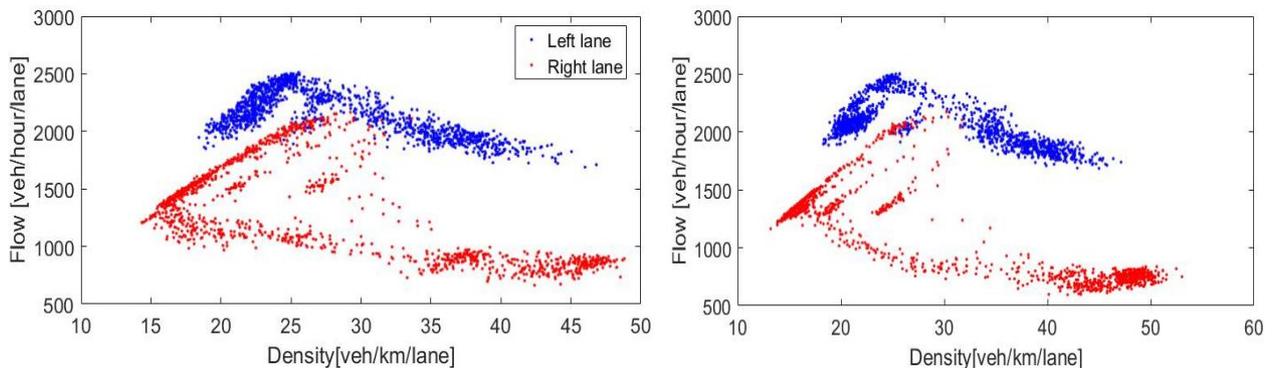


Figure 5.16: Effects of allowing yielding on traffic states in the fundamental diagram: 'fixed gaps' strategy (left) vs. 'allow yielding' strategy (right) (100% pen. rate).

5.2.2 Effects of allowing courtesy lane changing

The effects of truck platooning on traffic performance and safety were also researched for the situation that the truck platoons cannot yield for merging vehicles, but can perform a courtesy lane change to the left to create a gap for merging vehicles. If platoons are allowed to perform such lane changes, the results do not change in free flow compared to if it is not allowed. This is because in practice hardly any trucks actually change lanes to the left because it is either simply too crowded in the left lane or the speed difference with the left lane is too high. Merge locations and merging speeds as well as the number of vehicles unable to merge in free flow are therefore not different from those described in section 5.1.

In congestion, however, there is a significant difference compared to the case in which the platoons are not allowed to change lanes. The number of vehicles unable to merge is significantly decreased with up to approximately 50% when all trucks are equipped. This results in a very slight reduction of the TTS, but the maximum outflow is not affected. The average speed difference between the left and the right lane becomes slightly lower because there is more interaction between the left and the right lane. However, this does not result in a different safety performance since the TE- and TI-TTCs and

the TTC and gap distributions remain the same as without allowing platoons to perform courtesy lane changes. The flow- and speed-contour plots and the fundamental diagrams neither reveal differences with the scenarios in which platoons could not change lanes. Concluding, apart from reducing the number of vehicles that are unable to merge in congestion, allowing platoons to perform courtesy lane changes does not change the effect truck platooning has on the traffic performance and safety on the motorway.

5.2.3 Effects of CACC time gap setting larger than the minimum accepted gap

The effects of truck platooning on traffic performance and safety were also researched for the situation that the truck platoons cannot yield nor change lanes for merging vehicles, but drive with a CACC time gap that is larger than the minimum gap that is accepted by human drivers as explained in sections 3.2.2 and 4.2.2. This allows on-ramp vehicles to merge between two trucks in a platoon. Merging vehicles, having full lane change desire at the end of the acceleration lane as explained in section 3.2.2 and **Appendix D**, will then accept merging within a truck platoon just before the acceleration lane is exceeded. This was simulated for a CACC gap of 0.9 s. It has the effect that more vehicles are able to merge successfully in free flow. The reduction of the number of vehicles unable to merge in case of a CACC time gap of 0.9 s compared to 0.7 s is approximately 35-60% in free flow. The effect is only slightly larger with increasing penetration rate. During congestion, an effect on the merging behaviour is not observed. Similar to the 'allow yielding' strategy, the CACC time gap of 0.9 s reduces the effects of truck platooning on the TTS and the maximum outflow, but the differences with the 'fixed gaps' strategy in combination with smaller time gaps as described in section 5.1 are now smaller. This also applies to the other performance indicators. Concluding, a CACC time gap larger than the minimum gap accepted by merging vehicles has similar but smaller effects on traffic performance and safety as the 'allow yielding' strategy. Hence, the 'allow yielding' strategy is more effective in solving merging problems than applying a larger CACC time gap.

5.3 Conclusions

Based on the results presented in section 5.1.2 it is concluded that truck platooning makes merging more difficult. Many more vehicles merge in the last 50 m of acceleration lane and many may be unable to merge in time. This problem gets worse as there are more truck platoons. Apart from the number of truck platoons, the on-ramp traffic intensity is most determining for the severity of merging problems. Although vehicles that are not able to merge in time are simply deleted in the simulations, in reality they will still need to merge, which they could either do from standstill with a very high collision risk or by driving on the shoulder lane, causing other safety issues. This may lead to increased disruptions in the traffic flow, deteriorating the initial outflow benefit implied by truck platooning. Also, on average, merging speeds drop by approximately 10 km/h in the last 50 m of acceleration lane in the case of free flow. At medium to high traffic intensities, this drop is larger as more truck platoons are present. In free flow, the average merge location and merging speed are mostly independent of the platoon configurations. They depend almost entirely on the traffic intensity.

As shown in section 5.1.3, truck platooning hardly affects traffic flow in terms of TTS and maximum outflow in free flow conditions. The congestion scenarios however reveal a potential road capacity increase of 2% with 200 equipped trucks/h up to 19% with 800 equipped trucks/h on average. This is caused by higher flows in the right lane. The congestion also becomes less severe: it takes longer to form and speeds are higher. Furthermore, in congestion, the inhomogeneity of traffic states across the lanes increases a lot. This is because traffic in the left lane does not break down as much as in the base scenarios, possibly caused by the fact that truck platoons will not change lanes. These speed differences could potentially lead to dangerous situations.

An overview of the differences in traffic performance and safety effects between the different platooning strategies and platoon configurations is given in Table 5.3. Larger platoon sizes increase merging problems considerably, also at lower traffic intensities and penetration rates. However, at the same time the capacity in case of a maximum platoon size of three trucks instead of two trucks can increase with up to 8% extra, but the increase is only significant for penetration rates above 25%.

As long as CACC time gaps applied by truck platoons are smaller than the minimum acceptable gap for merging vehicles, the number of vehicles unable to merge in time will considerably increase with increasing CACC time gap. This effect is largest for high and medium traffic intensities. A CACC time gap of 0.3 s results in an extra capacity increase of 1-2% maximum compared to 0.7 s when all trucks

are equipped. A summarizing overview of the effects of truck platooning on traffic performance and safety is given in Table 5.2.

Concluding, the fact that vehicles are deleted when unable to merge in time can be a large limitation to the validity of the results. In reality these vehicles will still need to merge, causing more disruptions in the traffic flow. Therefore the effects of truck platooning for the other platooning strategies (see section 4.2.1) and a larger CACC time gap, allowing more vehicles to merge were also researched.

Based on the results presented in section 5.2.1, it is concluded that allowing truck platoons to yield for merging vehicles reduces the effects of truck platooning on traffic. Most importantly, allowing yielding solves merging problems as all vehicles are now able to merge in time. The yielding does not lead to extra unsafety on the motorway. The results also reveal that the positive effects of truck platooning on traffic flow performance still hold when yielding is allowed, even though the effects are smaller because more vehicles are merging. Thereby it must be noted that the 'allow yielding' strategy requires truck drivers to take over control instantly when not paying attention. In reality however, a long time may often be needed to successfully complete this transition of control. In that case it is already too late to yield for a merging vehicle. Hence, automatic gap creation is to be preferred to ensure that the truck platoons take action on time.

Given the findings from section 5.2.2, it is concluded that the 'allow lane changing' strategy is also able to reduce merging problems, but only in congestion. In free flow the speed difference with the left lane is simply too large for the truck platoons to be able to change lanes safely. Thereby it must be noted that a platoon member driving at a small gap to its predecessor has a reduced forward-view and hence might be unlikely to change lanes in reality. Similarly, as found in section 5.2.3, truck platoons driving with a CACC time gap larger than the minimum gap accepted by merging vehicles can also reduce merging problems, but only in free flow. However, as explained in section 4.2.2, driving at larger time gaps may be undesirable since it will cause cut-in lane changes, thereby disengaging the platoon. Concluding, the 'allow yielding' strategy is the most effective solution to the merging problems implied by truck platooning with the 'fixed gaps' strategy.

Table 5.2: Effects of truck platooning on traffic performance and safety compared to the base scenarios.

	Free flow	Congestion
Merge location distributions	More vehicles merge in last 50 m, up to 30 veh/h unable to merge in time depending on pen. rate and intensity.	Similar to free flow, but now up to 60 veh/h unable to merge in time.
Merging speed distributions	Average drop of 10 km/h in last 50 m. At medium to high intensity the drop is slightly larger with increasing pen. rate.	Minor average increase (< 10 km/h) in last 50 m that is slightly larger with increasing pen. rate.
Gap distributions	Very minor reduction of average gaps maintained at the on-ramp area, likely caused by behavioural adaptation.	Similar effects as in free flow.
Time-to-collision distributions	Similar to base scenarios, still no unsafe situations observed.	Significant reduction in TE-TTC and TI-TTC values.
TTS	Minor reduction with increasing pen. rate (max. -2%). On-ramp intensity is most determining for the effect.	Reduction with increasing pen. rate (max. -16%).
Max. outflow	Similar to TTS effects.	Linear capacity increase with increasing pen. rate is observed (max. +19%). Only significant for pen. rate > 25%.

	Free flow	Congestion
dVLane	Similar to TTS effects, but the reduction is now highest for lower traffic intensities.	Significant near-linear increase (up to +135% at max. pen. rate), especially because traffic in the left lane does not break down as much.
Flow- and speed-contour plots and fundamental diagrams	No significant differences in flows and speeds compared to the base scenarios.	Congestion becomes less severe. The onset of congestion is delayed and minimum flows (up to max. +250 veh/h) and speeds (up to max. +5 km/h) are higher. Large increase in maximum flow in the right lane (up to 21% at max. pen. rate).

Table 5.3: Overview of differences in effects between platooning strategies and platoon configurations.

Platooning strategy/configuration	Traffic performance effects	Traffic safety effects
Maximum platoon size	Larger platoons potentially increase capacity for higher pen. rates (2 vs. 3 trucks = max. +8%) and avg. speed difference across the lanes (+5%).	Larger platoons considerably increase merging problems (2 vs. 3 trucks = +50-100% more vehicles unable to merge in time)
CACC time gap < critical gap	Smaller time gaps potentially increase capacity (0.3 vs. 0.7 s = +1-2%).	Larger gaps considerably increase merging problems, especially at medium to high intensity (0.3 vs. 0.7 s = up to 3x more vehicles unable to merge at 100% pen. rate).
CACC time gap > critical gap	In line with effects of smaller gaps.	Merging problems are significantly reduced (0.7 vs. 0.9 s = -35-60% in free flow).
Allow yielding	Platooning effects on traffic flow are reduced. Traffic in the right lane gets disrupted more due to merging vehicles.	Solves merging problems completely, all vehicles are able to merge in time.
Allow lane changing	Little to no effect because there is little opportunity to actually change lanes.	Reduces merging problems, but only in congestion (up to 50% for high pen. rates)

6 Conclusions and recommendations

This final chapter provides conclusions on the main findings in section 6.1, thereby answering the research questions. The next section 6.2 discusses the most important limitations of this study, thereby providing the contexts in which the conclusions are valid. A reflection on the conduction of the research is given in section 6.3. Finally, recommendations for practice and for further research are made in section 6.4.

6.1 Conclusions from findings

The main goal of this research was to gain insight into the impacts of truck platooning on traffic performance and safety at motorway on-ramps in mixed traffic. To achieve this, the following main research question was formulated:

What are the traffic performance and safety effects of truck platooning on the motorway in the situation of conventional vehicles merging at an on-ramp for different platooning strategies and platoon configurations?

This main research question was answered by designing a traffic simulation environment that can successfully simulate and evaluate these strategies and configurations and that was used to compare and evaluate the traffic performance and safety effects. Thereby this research will hopefully help to facilitate the introduction of automated truck platoons on the motorway in the Netherlands and abroad and shed some light on the challenges related to this introduction for road authorities and other stakeholders.

Several steps were taken to arrive at the answers. Firstly, an elaborate literature study was conducted. Automated driving (AD) controller frameworks were researched to determine which one was best applicable for application by truck platoons. The shortcomings of the frameworks were carefully considered and possible solutions to these shortcomings were suggested. The most important shortcoming was found to be the absence of a safety mechanism that can handle critical situations. Next, existing human driving behaviour models were researched to determine their performances and more specifically their suitability for modelling motorway merging behaviour. Considering car-following behaviour, especially the Wiedemann model and the IDM+ seemed suitable. Considering lane change behaviour, the LMRS proved to perform best, especially because it incorporates relaxation and synchronization behaviour and a more realistic lane change decision structure. Existing traffic simulation platforms were also researched with the goal of finding the one most suitable to adapt and extend to incorporate automated driving and to simulate with. Behavioural adaptation of human drivers in the presence of truck platoons was researched as well. The most important finding from this is that human drivers will accept smaller gaps when merging in front of or within truck platoons.

Given the results from the literature study, MOTUS was chosen as simulation platform and extended to include automated driving to enable truck platooning. The human driving model parameter values applied were calibrated and validated for a Dutch motorway in other research, so that the validity of the modelling was guaranteed. The performance of several AD controllers was first tested using simulation in typical driving scenarios and a controller using a constant time gap strategy with single predecessor anticipation and incorporating a collision avoidance system was implemented in MOTUS. Also, the human driving behaviour was adapted to incorporate the behavioural adaptation found in the literature study where possible. By analysing traffic flow characteristics as well as analysing the truck platoon driving behaviour in detail, the ability of the extended model to generate plausible driving behaviour was tested. This resulted in tuning of the AD controller model parameters so that the automated driving behaviour became smooth and collision-free.

In this research, truck platoons were simulated with different characteristics. Firstly, different truck platooning strategies are distinguished: a strategy in which the platoon members always remain coupled, regardless of the needs of other traffic, a strategy in which the platoon members are allowed to create a gap for merging vehicles if they recognize the need of a vehicle to merge and a strategy in which platoon members are allowed to change lanes. Secondly, different platoon configurations are distinguished: Two different maximum platoon sizes (2 and 3 trucks) and four different platoon inter-vehicle gaps (0.3, 0.5, 0.7 s and 0.9 s). In order to capture platooning effects in a wide range of traffic conditions, also four different traffic intensities (low, medium, high and congestion) as well as

four different penetration rates of equipped trucks (25, 50, 75 and 100%) were researched. The simulations were applied on a two-lane motorway stretch with one on-ramp and a 350 m long acceleration lane.

The main finding is that truck platooning at motorway on-ramps makes merging more difficult. The merge locations are shifted slightly more towards the end of the acceleration lane and merging speeds in the last 50 m of the acceleration lane can be approximately 10 km/h lower on average. Some vehicles will exceed the acceleration lane. This problem gets larger as more truck platoons pass the on-ramp and as the traffic intensity on the on-ramp increases. The share of merging vehicles that is unable to merge in time is mostly independent of the traffic intensity. At penetration rates below 25%, less than 1% of the merging vehicles is unable to merge. This may increase up to maximum 5.6% in free flow and 9.3% in congestion when all trucks are equipped. Depending on the traffic intensity, this corresponds to 1-4 vehicles/h for penetration rates below 25% and to approximately 60 and 90 vehicles/h in free flow and congestion respectively.

Larger platoon sizes and larger platoon inter-vehicle gaps increase merging problems considerably. With a maximum platoon size of three trucks and at high penetration rates, 50 to 100% more vehicles are unable to merge compared to a maximum platoon size of two trucks. This corresponds to a difference of approximately 15 to 35 vehicles/h. The difference is larger with increasing traffic intensity and penetration rate. The differences between the inter-vehicle gaps are even larger. With a platoon inter-vehicle gap of 0.7 s, in free flow up to three times and in congestion almost two times more vehicles are unable to merge compared to a gap of 0.3 s. This corresponds to a difference of approximately 35 vehicles/h in both cases. The largest increases occur in when the on-ramp intensity is high. Again, the differences are larger with increasing penetration rates. However, if platoon inter-vehicle gaps are applied that are larger than the minimum gap that a human driver accepts, merging problems are reduced again. With a gap of 0.9 s instead of 0.7 s, the reduction is already 35 to 60%. This corresponds to approximately 25 vehicles/h at maximum penetration rate. This is due to the fact that merging vehicles will accept that gap if they are almost out of acceleration lane. This improvement does not apply during congestion.

If platoon members are allowed to create a gap for merging vehicles, the merging problems are solved completely. Regardless of the traffic intensity and penetration rate, all vehicles are then able to merge in time. Allowing platoon members to change lanes does not solve the merging problems, but only reduces them with up to 50% at high penetration rates. This happens especially in congestion because trucks are then better able to change lanes.

Another finding is that even though truck platooning may increase merging problems at on-ramps, it may also lead to a road capacity increase. With 200 equipped trucks/h, the capacity increase found is approximately 2% on average. This increases up to 19% with 800 equipped trucks/h. This is mainly due to higher average flows in the right lane. It was also observed that congestion takes longer to form and average speeds in congestion are higher. However, this is partly caused by the fact that vehicles that are unable to merge are deleted and thus no longer disrupt the traffic flow. In reality, these vehicles would of course still have to merge at some point. The simulations in which truck platoon members are allowed to create a gap for merging vehicles yet reveal that a potential capacity increase of 15% with 800 equipped trucks/h still remains if all vehicles would merge in time. At the same time, the average speed difference between the left and the right lane slightly increases due to truck platooning. This may be undesirable from a safety point of view.

Summarizing, truck platooning at motorway on-ramps causes merging problems that are more widespread as there are more truck platoons, as the platoons are longer and as the traffic intensity on the on-ramp increases. Also at low penetration rates of equipped trucks, a significant number of vehicles is unable to merge in time. This problem can be solved by having platoon members yield to create a gap for merging vehicles. Allowing platoon members to perform courtesy lane changes or having the platoons drive at larger inter-vehicle gaps also reduces merging problems. Truck platooning can potentially increase road capacity, but the increase is only significant at high penetration rates. The severity of congestion can thereby be reduced and the onset of congestion delayed. It however can also lead to increased speed differences between the lanes in congestion, implying potential safety hazards.

6.2 Discussion

There are several important limitations of the results of this study. They are implied by lack of empirical data on truck platooning, the experimental design and the modelling framework used.

Limitations from the lack of empirical data on truck platooning

The most important limitation is the lack of validation of the adapted model. Although MOTUS was calibrated and validated for the standard model without truck platooning and the adapted model was loosely validated using empirical evidence on motorway traffic in general, there is no empirical data on truck platooning in mixed traffic that is suitable to validate the adapted model. Part of this problem has been tackled by analysing a driving simulator study revealing behavioural adaptations of human drivers as well as analysing human driving behaviour at busy motorway freight routes with lots of non-automated truck platoons in section 2.3 of the literature study. However, the information obtained from these studies cannot fully capture the effects of truck platooning on driving behaviour because of a lack of quantitative data and incompleteness. To achieve that, one would need real-life quantitative data of truck platooning at motorway on-ramps in mixed traffic.

This means that any behavioural adaptation of human drivers in the presence of truck platoons, other than what is already known from aforementioned research, could not be taken into account. Worse still, not even all that is already known on this behavioural adaptation could be taken into account given the capabilities of the human driving behaviour models: behavioural adaptation in the sense that human drivers maintain a significantly shorter gap in the neighbourhood of truck platoons is not taken into account. This means that the effects of truck platooning on safety could be worse.

Limitations of the experimental design

An important limitation of the experimental design is the platooning strategy in which platoon members are allowed to create a gap for merging vehicles. It requires truck drivers to take over control instantly when not paying attention. The time that people need to become aware of the situation when transition of control is necessary is often highly underestimated. In reality, a long time may often be needed to successfully complete this transition of control, but too little empirical data is available to identify and quantify the effects of vehicle automation on driver performance. In that case it is already too late to yield for a merging vehicle. Hence, this is not a good strategy to use in practice; one would rather prefer automatic gap creation to ensure timely action. Similarly, it may be unlikely that platoon members will actually perform courtesy lane changes in reality if they are driving at a small time gap with their predecessor, since their forward-view is mostly blocked by the predecessor.

Another limitation of the experimental design is the fact that platoon formation is 'on-the-fly', i.e. equipped trucks will only form platoons if they happen to be driving close to each other. This limits the number of platoons that are formed, as reflected by the fact that even when all trucks are equipped, still less than 20% of them actually drive in platoons. If the travel times of equipped trucks would be planned beforehand, this could be much higher. Thereby the share of platoons that actually is the maximum size could also increase. The effects of truck platooning would then also be larger.

Limitations of the modelling framework

There are also several limitations of the results implied by the human driving behaviour modelling in MOTUS. With the LMRS lane change model, drivers only consider the vehicles directly surrounding them to evaluate a lane change decision. In reality, human drivers are often very good at anticipating and may look ahead or backward hundreds of meters. This allows them to for instance observe a suitable gap behind them when merging at an on-ramp. In the simulations however, it was observed that merging vehicles synchronize with a passing truck platoon and eventually fail to merge, even though there was plenty of room both in front and behind the platoon. These vehicles failed to recognize these merging possibilities, which would obviously not have happened in reality. This limitation might lead to a slight overestimation of merging problems in the simulation results.

There is another model limitation related to lack of anticipation. Anticipation of vehicles on the motorway on merging traffic at the on-ramp by changing lanes to the left before reaching the on-ramp is not taken into account, even though this is observed very frequently in reality. This could lead to a slight overestimation of merging problems because too many vehicles are still in the right lane.

Another important limitation is that in MOTUS, vehicles are deleted if they can no longer follow their desired route. This happens when vehicles are unable to merge in time so that they exceed the acceleration lane. In reality, these vehicles would either stop at the end of the acceleration lane or continue driving on the shoulder lane. At some point, these vehicles will still merge, causing additional disruptions in the traffic flow. These are not accounted for in the simulations. This leads to an overestimation of the positive effects of truck platooning on traffic flow as well as an overestimation of safety. Therefore, when comparing any of the performance indicator values, the number of deleted vehicles should always be kept in mind. However, the platooning strategy in which the platoon members were allowed to create a gap for merging vehicles revealed that even when no vehicles are deleted any more, the platooning effects found still remain, even though they have become slightly smaller.

The sensitivity of the simulation results to changes in human driving behaviour model parameters has not been investigated. In this research, apart from the minimum accepted gap, the standard calibrated values of the IDM+ car-following model and the LMRS lane change model were used. Although these standard values should not be deviated from too much in order to keep the model valid, small changes in parameter values might still have a significant effect on traffic flow characteristics. In other research, it has been revealed that traffic flow characteristics are especially sensitive to the minimum accepted gap setting, while they are mostly insensitive to other parameter settings (Calvert et al. 2017). Although the minimum accepted gap setting was carefully determined in this study, a sensitivity analysis of the results by varying this setting is lacking.

Finally, the IDM+ and LMRS model parameter values applied have only little stochasticity, so that little variation in driving behaviour between drivers is realised. Only for the desired speed, stochasticity is applied. Adding more stochasticity in the model parameters could make the driving behaviour more realistic. For example, elderly would show different merging behaviour than younger people and people that are familiar with the surrounding area would show different behaviour than people unfamiliar with it. The complexity of the road design is also of large influence on this behaviour. The sensitivity of the simulation results to this parameter tuning has however not been quantified and therefore it must be kept in mind that results may be slightly different if more stochasticity would be added. Also, human behavioural and psychological traits such as perception errors, reaction time and risk assessment are lacking in the IDM+ car-following model, limiting the degree to which the driving behaviour displayed is realistic.

6.3 Reflection

Truck platooning has become quite a hot topic in recent years and many research is conducted or is planned. Among this research are field tests and in a few years commercial use can even be expected. However, the literature review conducted in this study revealed that little information is available on what kinds of AD systems truck OEMs actually use or plan to use in their trucks. This made it necessary to make the assumption of a controller with constant time gap strategy. Fortunately, this choice could be verified by an expert in the field, confirming the validity of this important assumption. Similarly, assumptions were made for behavioural adaptation, since there is simply too little literature that covers and quantifies these effects. Again, the assumption of the acceptance of smaller gaps could be verified by several experts in the field at Rijkswaterstaat, confirming the validity of this important assumption.

Apart from using my network to verify the necessary assumptions, a major challenge of this research was correctly programming MOTUS and Matlab such that the desired situations were simulated and evaluated. Concerning MOTUS, especially programming the platooning conditions and the interaction with lane changing and other vehicles correctly was a big challenge. Thankfully, the developer of MOTUS at TU Delft was of great and indispensable help in answering my questions and giving suggestions. Still, however, it was a time-consuming process that required a high understanding of the model structure. Also, data management became a very important issue. The large number of simulation scenarios produced an enormous amount of data and figures that had to be automatically labelled and saved in the correct folders and subfolders. Several improvements to the data management had to be made during the process to prevent mix-ups and unwanted deletion of data. Also, efficient ways of data saving had to be used to prevent the amount of data becoming too large and the duration of the simulations too long. Concerning the acquisition of the desired figures and performance values, a lot of trial and error and debugging was necessary before the output became as desired. Looking back, the amount of time required for programming was underestimated. Although I

knew little of programming at the start, this research certainly helped to improve my programming skills a lot.

Finally, time constraints implied a limitation to the number of performance indicators that could be researched. Ideas for additional indicators were formed to complement the indicators used, such as the total number of lane changes and the average vehicle delay, but in the end there was too little time to analyse the results, so these had to be omitted. Therefore, a more complete picture of traffic performance and safety could still be achieved.

6.4 Recommendations

In this section, practical recommendations are first made that can be used by road authorities for determining a policy on truck platooning. Recommendations for further research are also made to serve as a guideline for future research on truck platooning effects on traffic performance and safety.

6.4.1 Recommendations for practice

It has been shown that the introduction of truck platoons on the motorway will lead to merging problems at on-ramps. As long as there are still few equipped trucks, merging problems are marginal at low traffic intensities. Therefore truck platooning at motorway on-ramps does not need to be discouraged when traffic intensities are low. This means a time frame could be implemented, for example allowing truck platooning at on-ramps only during night time. At higher traffic intensities, especially at high on-ramp intensities, truck platooning at on-ramps is not recommended. Even when still few equipped trucks are present, there will be vehicles that cannot find an acceptable gap. This will cause vehicles to either stop at the end of the acceleration lane or to proceed on the shoulder lane, which is undesirable and dangerous. A policy on whether truck platooning at motorway on-ramps is allowed could be based on the requirement that the number of vehicles unable to merge should not increase compared to the current situation without automated truck platoons. This requires empirical data research on the current performance of merging traffic at on-ramps.

A role for the infrastructure might emerge in providing information to automated vehicles behind the line of sight of the on-board sensors. In that way automated vehicles can be made aware of for instance potential merging issues when approaching an on-ramp, so that truck platoons can already increase their inter-vehicle gaps.

Although a platoon of three trucks causes significantly more merging problems than a platoon of two trucks, a platoon of two trucks still causes them as well, which is why truck platooning at on-ramps should be discouraged for higher traffic intensities, regardless of platoon sizes. It is recommended to limit the maximum platoon size allowed on the motorway based on the size that is considered acceptable by road users, but to define a policy that decides on where and when this is allowed at on-ramps. This is thus a rather flexible limit that may change over time. Given the literature findings and interviews with the Dutch road authority Rijkswaterstaat, this limit is currently three trucks.

Small platoon inter-vehicle gaps are desirable in order to prevent most cut-in lane changes, but these small gaps also proved to cause merging problems. Therefore a choice should be made: either allow truck platooning with small gaps while prohibiting it at on-ramps depending on the traffic intensity, or only allow truck platooning with larger gaps so that no problems are caused at on-ramps. The latter seems most unlikely because it will deteriorate the benefits of truck platooning. It is therefore recommended to allow truck platooning at time gaps as low as 0.3 s, but to prohibit it at on-ramps at higher traffic intensities.

An exception to a prohibition of truck platooning at on-ramps could be made if truck drivers are required by law to create a gap for merging vehicles when necessary. However, such a strategy could well prove itself ineffective since human drivers may take a long time to take back control after automated driving. Therefore, merging problems, although reduced would still be inevitable. This problem may be solved if truck OEMs are required to incorporate an automatic platoon disengagement system that recognizes forced merging. This also means that truck platooning on motorway sections with many on-ramps in close proximity of each other would become rather unattractive given the many formations and disengagements required at small time intervals.

Concluding, it should be determined what level of merging problems road authorities still find acceptable in order to determine the policy for truck platooning. Only after that, the solutions to merging problems caused by truck platoons can be established.

6.4.2 Recommendations for further research

Several recommendations for further research are proposed. Apart from general research recommendations, recommendations for road authorities and for improvements to the modelling framework constructed in this research are also proposed.

General recommendations

This research focused solely on the case of a motorway on-ramp. Impacts of truck platooning on other road sections is however also necessary in order to determine the total impact of truck platooning on motorway traffic. Interesting road sections could for instance be other discontinuities such as off-ramps and weaving sections. Especially at off-ramps, the sight on the signage and the ramp itself may be blocked by truck platoons, causing vehicles to miss their exit. Road sections with more than two lanes or with additional complexity in the road design, e.g. ramps close to each other, ramps at motorway intersections and ramps near tunnels could also be considered.

Moreover, additional research could be done by using additional performance indicators. There are many possibilities and each indicator has its pros and cons. Since each indicator only captures part of the characteristics of traffic, they need to complement each other to give a full picture of traffic. At the same time only a limited number of indicators can be chosen, so that some characteristics of traffic remain unknown. Therefore it might still be interesting to explore more indicators. An example is an indicator measuring the number of lane changes performed, so that the interaction between the lanes can be compared to the speed difference between the lanes. Also, instead of total time spent by all vehicles, a delay indicator could be used or an indicator giving the average time spent by vehicles.

Finally, the current research revealed knowledge gaps concerning behavioural adaptation of human drivers in the presence of truck platoons as well as the driving performance of partially automated vehicle drivers. Research that identifies and quantifies the behavioural adaptations using empirical evidence is desirable in order to improve the validity of simulation studies. This could also include research on whether truck drivers in a platoon will actually create a gap for merging vehicles at on-ramps and in what share of the cases they will.

For road authorities

In the coming years, a truck platoon facilitation strategy could be developed by road authorities. This could include a study of suitable time frames in which truck platooning at on-ramps is allowed. A method to have this information available in equipped trucks should then be researched, so that equipped trucks know when they have to disengage, since relying on the human driver may be very unreliable. This could involve installing road side units that communicate with equipped vehicles. One could take this even further by tuning the arrival times of truck platoons and merging vehicles, so that a merging vehicle will never arrive at the acceleration lane at the same time as a truck platoon. This would allow truck platooning at on-ramps even at higher intensities. Research could be done on the urgency to install such a system at particular on-ramps and the associated costs. To achieve this, co-operation with truck OEMs should be considered to harmonize the workings of the required technologies.

Of course, other measures that prevent merging issues altogether rather than solving them may also be researched. Changes to the road design are one option. An extension of acceleration lanes could for instance be considered. However, given the limited acceleration capability of vehicles, this may still lead to merging problems if the arrival times of the merging vehicle(s) and the truck platoon happen to be unfortunate. Another possibility is introducing a dedicated lane for automated vehicles or even for truck platoons only, or prohibiting truck platoons to drive in the right lane while allowing them to drive in the adjacent lane to the left. Such research should include cost-benefit analyses to quantify the costs and compare these with the gains.

Improvements to the modelling framework

Regarding the modelling framework created and applied in this research, a more complete validation is recommended by comparing with empirical data as soon as such data is available. Also, a sensitivity analysis of the model parameter settings could be conducted to further support the findings. Finally, adding more stochasticity to account for variability among drivers is recommendable for even more realistic results.

An extension to the modelling framework created in MOTUS could be the more realistic use of trucks with different acceleration and braking capabilities induced by differences in vehicle weight and the implementation of an AD controller that takes into account these differences by adjusting the desired time gap of trucks and using bi-directional communication. Research can then be done on the effects of these differences on the cohesion of the platoons and possible safety issues this might cause for other traffic, especially in situations with lots of variations in speed, such as in congestion shock waves.

Moreover, an improvement of car-following and lane change models is desirable to further improve the validity of simulations. The LMRS is already a relatively advanced model since it incorporates relaxation and synchronization, which is especially important for detailed analyses such as in this research. However, for the goal to improve the merging behaviour displayed, it is necessary to further improve the model. Another approach than deleting vehicles when they can no longer follow their desired route could be considered, for instance adding the possibility to proceed on the shoulder lane or to stop at the end of the acceleration lane. This could make merging behaviour more realistic. Also, adding the possibility to consider more vehicles for the lane change decision could result in more realistic anticipation of motorway vehicles on merging traffic and vice versa. Another improvement could be to add more stochasticity in the behavioural model parameters to account for more variability among drivers. MOTUS already has the option to add stochasticity to the existing parameters, but this is hardly used in the standard settings. The aforementioned human behavioural and psychological traits that are lacking in the IDM+ car-following model could also be added for a more realistic performance.

Concluding, although modelling automated driving behaviour might be relatively straight-forward and the human driving behaviour models IDM+ and LMRS already are an improvement compared to other models, modelling the response of human drivers to automated vehicles is certainly not easy because of the knowledge gaps on behavioural adaptation as well as missing human factor aspects in the current human driving behaviour models. Therefore, additional research on behavioural adaptation in the presence of automated vehicles and incorporation of more human factors in human driving behaviour models are needed more than ever in order to be able to determine the impacts of automated driving in general and of truck platooning at motorway on-ramps more specifically.

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Appendix A

ACC gap regulation strategies

This appendix gives a description of the mathematical definitions of the ACC controller gap regulation strategies that are not given in the report. It also provides a more detailed description of some of the strategies.

A.1 Constant distance gap

According to (Wang 2014), the algorithm for the CDG strategy is as in **equation (A.1) and (A.2)**.

$$a_{i,t} = k_s (s_{i,t} - L) + k_{\Delta v} (v_{i-1,t} - v_{i,t}) \quad (\text{A.1})$$

with

$$s_{i,t} = x_{i-1,t} - x_{i,t} - l_i \quad (\text{A.2})$$

Where:

$a_{i,t}$: desired acceleration of vehicle i at time t [m/s²]

$k_s, k_{\Delta v}$: control parameters for the gap error and the speed error respectively

$s_{i,t}$: distance gap of vehicle i with vehicle $i-1$ at time t [m]

L : fixed desired distance gap [m]

$v_{i-1,t}, v_{i,t}$: speed of vehicle $i-1$ and vehicle i at time t respectively [m/s]

$x_{i-1,t}, x_{i,t}$: rear bumper position of vehicle $i-1$ and vehicle i at time t respectively [m]

l_i : length of vehicle i [m]

The first term on the right hand side of **equation (A.1)** ensures that if the actual gap is smaller than the desired gap, the acceleration will decrease or become negative until the actual gap has sufficiently increased. The second term ensures speed synchronization with the vehicle directly in front of the vehicle in question.

A.2 Variable time gap

The equation for calculating the desired acceleration is the same as that of the CTG strategy (**equation (2.1)**). However, now the desired gap is a quadratic function of speed as in **equation (A.3)** with similar definitions of the variables as in **equation (A.1)**.

$$s_{i,des,t} = z_1 v_{i,t} + z_2 v_{i,t}^2 + s_0 \quad (\text{A.3})$$

Where:

z_1, z_2 : control parameters

A.3 Safe distance control

If the actual gap is smaller than the safety gap, the desired acceleration can be given by **equation (A.4) and equation (A.5)** (Wang 2014) with similar definitions of the variables as in **equation (A.1)**.

$$\text{For } s_{i,t} < s_{safe,t} : a_{i,t} = -2 \frac{s_{safe,t} - s_{i,t}}{T_{u,prev}^2} \quad (\text{A.4})$$

with

$$s_{safe,t} = s_0 + v_{i,t} \tau + \frac{v_{i,t}^2}{2b} - \frac{v_{i-1,t}^2}{2b'} \quad (\text{A.5})$$

Where:

$s_{safe,t}$: safety distance at time t [m]

$T_{u,prev}$: control parameter [$1/s^2$]

τ : time lag [s]

b, b' : braking capabilities of the ACC vehicle and its predecessor respectively [m/s^2]

If the actual gap is larger than the safety gap, the desired acceleration is determined by the CTG strategy, i.e. **equation (2.1)**.

A.4 Based on IDM and OVM

The Intelligent Driver Model (IDM) calculates the desired acceleration as in **equation (A.6)-(A.8)** (Wang 2014).

$$a_{i,t} = a_{\max} \left(1 - \left(\frac{v_{i,t}}{v_{des}} \right)^{\delta} - \left(\frac{s_{i,des,t}}{s_{i,t}} \right)^2 \right) \quad (\text{A.6})$$

with

$$s_{i,des,t} = s_0 + \max \left(0, v_{i,t} t_{des} + \frac{v_{i,t} (-\Delta v_{i,t})}{2a_{\max} b_{\text{conf}}} \right) \quad (\text{A.7})$$

$$\Delta v_{i,t} = v_{i-1,t} - v_{i,t} \quad (\text{A.8})$$

Where:

a_{\max} : maximum acceleration [m/s^2]

v_{des} : cruising (desired) speed [m/s]

δ : model parameter

$s_{i,des,t}$: desired distance gap of vehicle i with vehicle $i-1$ at time t [m]

$\Delta v_{i,t}$: relative speed difference of vehicle i with vehicle $i-1$ at time t [m/s]

b_{conf} : comfortable deceleration [m/s^2]

The first two terms between brackets of **equation (A.6)** indicate the desired acceleration based on the desired speed (cruising speed), while the last term indicates a correction of the desired acceleration based on interaction with the predecessor. **Equation (A.7)** prevents the ACC vehicle from colliding with its predecessor.

The OVM approach calculates the desired acceleration as in **equation (A.9)**.

$$a_{i,t} = \alpha (v_{opt}(s_{i,t}) - v_{i,t}) \quad (\text{A.9})$$

Where:

α : sensitivity factor

v_{opt} : optimal velocity (function of the distance gap) [m/s]

Appendix B

Human driving behaviour models

This appendix provides information on longitudinal and lateral driving behaviour models. First, car-following models are discussed and subsequently lane change models are discussed. A model that combines longitudinal and lateral driving behaviour in an integrated model is also briefly discussed. A summarizing overview of the most important characteristics of the models is given in Table 2.3 for the car-following models and in Table 2.4 for the lane change models discussed.

B.1 Car-following models

Existing car-following models can be classified into the eight main groups that are given in the next subsections. The existing models of each group are briefly discussed.

B.1.1 Stimulus-response models

The first group of car-following models is stimulus-response. These models are formulated as a stimulus-response equation. The main acceleration and deceleration stimulus of a vehicle is the relative speed of the vehicle and its predecessor. The driver reaction time is also taken into account. It also incorporates control parameters for calibration. Numerous enhancements of the basic stimulus-response model as formulated by **General Motors** Group in the USA in the 1950s have been proposed (Broekman 2017), (de Azevedo 2014). Many of these models have no thresholds and thus vehicles react to every minor change in one of the stimuli. Obviously, this is not always realistic. The model enhancements mainly add more heterogeneous driver behaviour by introducing different stimulus-response sub-models. The mathematical algorithms of some important stimulus-response models are given in (de Azevedo 2014).

A **Gazis-Herman-Rothery (GHR)** model (Brackstone and McDonald 1999) determines the vehicle's acceleration and deceleration using the current speed of the vehicle and the speed difference and distance gap between the vehicle and its predecessor.

(Ahmed 1999) describes acceleration behaviour using a time gap threshold. This threshold and the reaction time of drivers have a distribution to take into account variability among drivers. The acceleration behaviour is different in free flow conditions than in car-following conditions. The transition between those two stages is not smooth. The car-following model from Ahmed is used by the simulation software platform MITSIMLab.

Older models assume that drivers accelerate when the preceding vehicle is driving at a higher speed and vice versa. However, (Koutsopoulos and Farah 2012) found that in many cases the opposite is true. They propose a model with three driving states: accelerating, decelerating and doing nothing as an extension of the GHR model. Statistical tests show that their model performs better than the GM model (Broekman 2017).

B.1.2 Collision-avoidance models

Collision-avoidance models are based on a safe following distance. This safe following distance is required to avoid a collision with the predecessor. It is a function of the speed of the vehicle and its predecessor and the driver's reaction time. It also incorporates control parameters for calibration. Similar to stimulus-response models, collision-avoidance models state that vehicles react to their predecessor. However, now vehicles react depending on the distance gap between the vehicle and its predecessor rather than the speed difference. Enhancements to the basic collision-avoidance model have been proposed, such as adding driving behaviour variability. In more recent research it was found that often the assumption that drivers follow their predecessors at a safe distance is frequently not respected (de Azevedo 2014).

A popular and well-known model of this type is the **(Gipps 1981)** model. In this model, vehicles accelerate or decelerate depending on the distance gap with its predecessor in such a way that a collision is avoided might the predecessor suddenly brake. The model includes both driving behaviour for free flow conditions as well as car-following conditions. For every time step it calculates both and

applies the lowest speed calculated. The model takes into account several behavioural parameters such as desired acceleration and deceleration, desired speed and reaction time. These parameters have stochasticity, i.e. are drawn from a distribution to include heterogeneity among vehicles. An important adaptation of the Gipps model was created by Hamdar and Mahmassani (2008), see Appendix B for more information.

A special kind of collision-avoidance model is a **desired measures model**. It uses for instance desired spacing, desired time gap and/or desired speed to determine acceleration or deceleration. A maximum for the acceleration and deceleration is defined to keep the vehicle behaviour within realistic limits.

An example of a desired measures model is the **Intelligent Driver Model (IDM)** (Treiber et al. 2000). This model uses one equation to describe free flow and car-following conditions. This allows a smooth transition between free flow and car-following conditions and a better replication of the traffic hysteresis phenomenon (de Azevedo 2014), which is not achieved by the model of Ahmed. A driver reaction time is not taken into account, causing instantaneous reaction to changes of the driving conditions. This is obviously not very realistic. The mathematical algorithms of some important collision-avoidance models are given in (de Azevedo 2014).

(Hamdar and Mahmassani 2008) adapted the Gipps model to include the possibility of colliding vehicles by relaxing some constraints such as a distributed safety threshold that varies among vehicles. Incidents can occur as model equations and input variables are changed (Broekman 2017).

Extensions and adaptations of the IDM have been created. The **IDM+** (Schakel et al. 2010) (Schakel et al. 2012) is an adaptation that achieves more reasonable capacity values by changing the equation of the desired acceleration. The IDMM (2003) has a memory function that allows vehicles to adapt their driving behaviour. This means that when congestion occurs vehicles adapt their driving behaviour after 600 seconds. This threshold can also be changed. Since all drivers have this same threshold, the driving behaviour displayed can be rather deterministic. Moreover, the model assumes that the desired time gap is influenced by the level of service of the vehicles' current lane. Another extension is the Human Driver Model (HDM) (2006). This model includes reaction times, estimation errors, spatial anticipation and temporal anticipation. These adaptations allow a more human-like driving behaviour (Broekman 2017).

B.1.3 Linear models

Another type of models are the linear models. These models are straight-forward and easy to understand. **Helly (1961)** (Brackstone and McDonald 1999) proposed such a model. The desired acceleration thereby is a linear function of the desired following distance, the relative speed of the vehicle and its predecessor and the inter-vehicle gap. It also incorporates control parameters for calibration. The driver's reaction time is also incorporated in the model. The linear responses to deviation from the desired gap and desired speed do not result in realistic shockwave patterns (Schakel et al. 2010). The model originated from the previously named GHR model. The model was found to present a good fit to observed data (de Azevedo 2014). It was mainly applied to low speed urban networks. An advantage is the incorporation of an error component, namely a possible rejection of the computed acceleration when the inter-vehicle gap is substantially different from its expected value. Many variations of the Helly model exist. The mathematical algorithm of the Helly model is given in (de Azevedo 2014).

B.1.4 Psycho-physical models

All previous models assume that drivers react to every minor change in the relative speed with the predecessor. They also assume that drivers react to these changes even if the distance gap is very large. Models that overcome these unrealistic assumptions are psycho-physical models. They do so by introducing different driving regimes for which different driving behaviour is assumed.

The most familiar psycho-physical model is the model introduced by **Wiedemann (1992)** (Olstam and Tapani 2004). It has four different regimes: free driving, closing in, car-following and emergency. In the closing in regime, the vehicle has a higher speed than its predecessor and consequently the gap between them decreases. Thresholds are defined so that vehicles will not react to every minor change in speed or gap. It assumes that at large following distance, drivers are not influenced by the amount

of speed difference. Also, at small following distance, drivers are not influenced by the amount of speed difference if the relative difference in speed is too small. The model takes into account the stochastic acceleration and deceleration behaviour that exists in reality. Many extensions and enhancements of the model have been proposed (de Azevedo 2014, Broekman 2017).

The Wiedemann model is used in many simulation case studies and is the longitudinal model applied in microscopic simulation platform VISSIM (see also section 2.2.3). Research by (Oud 2016) indicated quite a good performance of this model for the considered situation (around motorway ramps).

B.1.5 Optimal velocity models

Optimal velocity (OV) models determine the acceleration of a vehicle based on the difference between its current speed and its optimal (or desired) speed. This optimal (or desired) speed depends on the gap with the predecessor. It also incorporates a control parameter for calibration. Only one equation is needed to describe both free flow and car-following conditions. Although this model is able to replicate first-order macroscopic traffic flow variables, it fails to replicate heterogeneous driving behaviour (de Azevedo 2014). The OVM is not always collision free and performs worse than the IDM in representing trajectory data (Schakel et al. 2010).

An extension of the OV model is the **Full Velocity Difference** (FVD) model (2001). In addition to the variables used in the OV model, it also takes into account the relative speed of the vehicle and the predecessor. Acceleration and deceleration behaviour is similar, which can lead to some unrealistic behaviour. To solve this issue, the **Asymmetric Full Velocity Difference** (AFVD) model (2008) was introduced. It adds sensitivity coefficients for acceleration and deceleration which allows asymmetric driving behaviour. This also means that more computation time is needed before a stable traffic state is reached in simulation.

A model as proposed by (Lenz et al. 1999) can also be regarded as an extension of the OV model. It adds multi vehicle interactions to increase stability. It does not incorporate reaction times.

(Davis 2003) extended the OV model by allowing vehicles to change both their relative speed and gap. In that way the traffic flow remains stable for high reaction times as well (Broekman 2017).

B.1.6 Fuzzy logic models

Fuzzy logic models use logical rules to quantify decision alternatives. It is called fuzzy because vehicles do not know their exact position, speed and gap with the predecessor. Instead drivers are only able to check their state qualitatively (e.g. in a range of very low/low/moderate/high/very high) and change their behaviour accordingly. For example, a vehicle will check if it drives too close to the predecessor and if so, increase the gap by decelerating. Stochastic behaviour can be accounted for by using probabilistic density functions in the decision process. This kind of model has only been used scarcely.

B.1.7 Cellular automation models

Cellular automation models use a grid-based space system in which all types of driver behaviour are represented. The focus of such models up until now is however mainly on car-following behaviour only. They can provide a computationally efficient method for the simulation of large-scale networks, but they lack a detailed description of position, speed and gap with the predecessor due to a the lack of a proper coordinates estimation framework (de Azevedo 2014).

B.1.8 Prospect theory models

(Kahneman and Tversky 1979) developed a descriptive model estimating human decisions. These decisions are based on perception and judgement of a certain traffic situation and can thus vary among drivers. It takes into account the gains and losses of a certain choice. Weights are assigned to these choices rather than probabilities like in the utility theory. This model theory is known as the prospect theory (Broekman 2017).

(Hamdar and Mahmassani 2008) developed a behaviour theory based on the prospect theory. The most important variable of this model is the subjective probability of a driver to be involved in a

collision with its predecessor. This probability depends on acceleration, distance gap and speed difference. The utilities in this model are acceleration and deceleration. Vehicles will choose lanes according to the highest utility while taking into account the probability of a collision. Vehicle heterogeneity is achieved by determining acceleration from a probability density function.

B.2 Lane change models

Existing lane change models can be classified into the four main groups that are given in the next subsections. The existing models of each group are briefly discussed.

B.2.1 Rule-based models

Rule-based models are models for which the decision to perform a lane change is based on a predefined set of rules. They usually have a decision tree (hierarchical) structure.

One of the oldest lane change models of the rule-based type is that of (**Gipps 1986**). The driving behaviour depends on the answers to three questions: (1) is it possible to change lanes?, (2) is it necessary to change lanes? And (3) is it desirable to change lanes?. Several factors are defined that determine the answers to these questions, among which the physical possibility to change lanes safely, the location of obstructions, the presence of transit lanes, driver's intended turning movements, the presence of heavy vehicles and the speed of the vehicle and the surrounding traffic. The lane changing process is structured as a decision tree. Driver behaviour variability is not incorporated in the original model (de Azevedo 2014).

The model is intended to model lane changing in urban environments. A limitation of the model is that vehicles will only change lanes when the gap is sufficiently large and the manoeuvre is considered safe. In reality, other vehicles can react by for example increasing the gap size if necessary (Broekman 2017). Several adaptations and enhancements of the Gipps model have been developed throughout the years.

(**Halati et al. 1997**) developed a rule-based model which distinguishes not only mandatory and discretionary lane changes, but also random lane changes. These random lane changes are introduced to account for stochasticity. The mandatory lane changes are conducted to reach a planned destination, the discretionary lane changes are conducted to gain a speed advantage or a better driving environment and the random lane changes are those that are difficult to categorize. The structure of the model is similar to the Gipps model. The rules related to the three major questions are formulated as motion and spatial variables, such as the availability of acceptable gaps in the target lane, distance to exits and number of lane changes to exit. Acceptable gaps are modelled by defining the required deceleration to prevent a collision with the predecessor in the target lane. (Zhang et al. 1998) extended Halati's model by including a probability for the lane change action. This is more realistic since it ensures that drivers do not always change lanes even if it is beneficial.

(Hidas 2005) developed a similar model but included cooperative and forced merging. A vehicle executes a forced lane change when a sufficient gap is not available, thereby forcing the new follower in the target lane to decelerate. A limitation of this model however is that a cooperative lane change is only based on the decision of the rear driver.

In (**Van Aerde et al. 1996**) the executions of discretionary lane changes are determined by computing the potential speeds in the adjacent lane(s) and comparing those speeds to a threshold distribution for decision making.

A rule-based model by (**Wang 2005**) incorporates acceleration and gap acceptance and combines this with a model that describes cooperative vehicle behaviour of the vehicles on the motorway. The two different cooperative actions are cooperative lane changing and courtesy yielding. In the former case the vehicle on the motorway changes lanes to an adjacent lane, while in the latter case the vehicle on the motorway decelerates to enlarge the gap to the leader. The decision to make a cooperative lane change is determined by a binomial distribution and neglects the fact that it needs to be possible to perform the lane change, which is questionable. The courtesy yielding is also determined by a binomial distribution. This is more realistic because it is always possible for a driver to gradually decelerate. Moreover, the model can result in the inability of vehicles to merge, which happens in between 5 and 20% of the cases. Finally, upon completion of the lane change, normal car-following behaviour is applied. The validity of this is questioned in other research (Daamen et al. 2010).

Another model by (**Laval and Daganzo 2006**) incorporates the effect of lane changes on traffic flow. Empirical research shows that when congestion begins, lane changes trigger the discharge rate of bottlenecks. In further research, (**Laval and Leclercq 2008**) state that the most important effect of lane changes on traffic flow is the relaxation phenomenon. This is the acceptance of shorter gaps at the moment a lane change is performed and the subsequent increase of the gap to a normal value after a short period, usually 20 to 30 s. (Smith 1985) first empirically discovered this phenomenon. Any other attention for the phenomenon is scarce. Experiments by (Sultan et al. 2002) confirmed the existence of relaxation and the phenomenon was implemented in microscopic simulation tool FRESIM by (Cohen 2004). These studies do not allow quantitative effects of relaxation on traffic flow. It is plausible however that these effects exist. For example, a possible effect would be an overreaction of the merging vehicle and its new follower if relaxation is not included in the modelling.

A special kind of rule-based model is a **game theory** model. Game theory models (Kita 1999) are based on the 'give way' behaviour of vehicles in a merging situation. Vehicles taking part in the merging situation are regarded as 'players' which each a 'pay-off matrix' determining its strategy. Such models can also be considered rule-based.

Yet another kind of rule-based model is a **cellular automation** model. Cellular automation models use a grid-based space system in which all types of driver behaviour are represented. The focus of such models up until now is however mainly on car-following behaviour only. They can provide a computationally efficient method for the simulation of large-scale networks, but they lack a detailed description of position, speed and gap with the predecessor due to a the lack of a proper coordinates estimation framework (de Azevedo 2014).

The final type of rule-based model is a **hazard-based** model. Most lane change models do not consider stochasticity nor the risk of misjudging observational processes such as driver perception and judgement. (Hamdar and Mahmassani 2008) tried to overcome these problems by introducing a hazard-based lane change model. It is an improvement of the Gipps lane change model, like they also did for the Gipps car-following model. The model does not only take into account the leading vehicle, but also the follower vehicle. Two strategies are distinguished to determine whether a vehicle is in free flow, car-following or lane changing conditions. The first is the utility-based strategy where each of the three options has its own utility and the behaviour is chosen according to these utilities. The second strategy is the hazard-based strategy where each option is associated with a particular hazard score and the behaviour is chosen according to these scores. The model by Hamdar and Mahmassani is a simplified model of the Gipps model in the sense that it does not take into account a number of complex objectives of the Gipps model, possibly making it too simplistic for more complex situations.

B.2.2 Discrete choice models

Discrete choice models model lane change decisions based on the probability that a driver will execute a lane change given the utility of that lane change. These models can therefore also be classified as utility theory models with choice probability.

(**Yang et al. 1999**) proposed a model based on probability. Decisions are made based on a binary logit model (for mandatory lane changes) and depending on traffic variables from the current and target lanes (for discretionary lane changes).

A model developed by (Ahmed et al. 1996) uses a dynamic discrete choice model to capture driver behaviour variability. The discrete choice model is also used for forced merging. Logit models are used to model the decision process. Drivers first examine their satisfaction with the driving conditions of the current lane after which gap acceptance is modelled probabilistically. The model of Ahmed is applicable even in heavily congested conditions with a lot of forced merging manoeuvres as acceptable gaps are lacking. The boundary between discretionary and mandatory lane changes is very strict, which is not very realistic since in reality this boundary is rather vague. This strict boundary results in the presence of random lane changes. The mathematical algorithm of this model is given in (de Azevedo 2014).

The model by (**Toledo et al. 2007**) (see section B.3) can also be considered a discrete choice model.

(**Choudhury 2007**) uses a decision model based on driver's latent plans. Only the resulting actions from those plans are observable. Separate models are defined for the selection of a lane on the motorway, merging on the motorway at on-ramps and for lane selection on urban roads. The latent

plan of a merging vehicle consists of three phases: the normal state, the courtesy merge state and the forced merging state. Vehicles start in the normal state and can go to other states depending on the driving conditions. Each state has its own gap acceptance characteristics. In the normal state an acceptable gap is defined as being larger than the critical gap. The critical gaps have lognormal distributions, the mean gap is a function of explanatory variables.

This modelling framework consists of four layers: initiating courtesy merging, initiating forced merging, normal gap acceptance and gap acceptance of courtesy and forced merging. It is applicable for all general motorway situations but performs best when there is a large difference in the level of service among lanes.

The model differs from other models by taking into account state-dependence among decisions of a merging driver (Broekman 2017). This framework fails to model the phenomenon of cooperative lane changes. This might result in the number of acceptable gaps being underestimated. Moreover, merging drivers do not accelerate to reach the selected gap. This might lead to incorrect predictions of speeds and merge locations. Finally, it does not take into account the effect of lane changes on the traffic state as a whole. It is likely that especially due to courtesy and forced lane changes, this effect is different from standard longitudinal behaviour (Daamen et al. 2010).

(Kolen 2013) also defined a discrete choice model with the goal to overcome some limitations of earlier models. The analyses of the merging behaviour by (Daamen et al. 2010) namely show that gap acceptance theories in which a fixed critical gap is used is not able to model realistic driver behaviour. Therefore they proposed a new model theory. The idea is that every merging vehicle is able to find a suitable gap without being overtaken by multiple vehicles on the motorway and without coming to a standstill at the end of the on-ramp. A set of possible gaps is defined for every merging vehicle. A choice is then made based on a choice model. The choice depends on the style of the driver of the merging vehicle.

The elaboration of this framework required additional research. The choice model needed to be specified and the theory had to be calibrated. In 2013 such a choice model has been defined by (Kolen 2013).

B.2.3 Incentive-based models

In incentive-based models, the decision to change lanes depends on the desire (incentive) to do so. The desire (incentive) criterion measures the attractiveness of lanes. Multiple functions may be used to determine the level of desire depending on the road layout and traffic density.

The **Minimizing Overall Braking Induced by Lane Changes (MOBIL)** model (Kesting et al. 2006) is based on the Gipps model and lane change decisions are based on two criteria: the safety and the desirability of a lane change. It compares the attractiveness of a lane with the risk associated with changing to that lane in terms of acceleration. The decision to change lanes depends on the ability to improve the acceleration (Daamen et al. 2010). The computed accelerations are compared to a threshold value for final decision making. Only a small number of additional parameters are used in the model. Heterogeneity among drivers is accounted for by differing parameters for trucks and cars as well as taking a uniform distribution for the desired speed.

The attractiveness of a lane is expressed by a utility function for that lane that defines acceleration possibilities (Daamen et al. 2010). A politeness factor is also used to include the effect of the lane change on other vehicle's accelerations. This factor can be set from purely egoistic to purely cooperative and differently for mandatory and discretionary lane changes.

The model incorporates the 'keep right' rule by defining a passing rule and a lane usage rule. The passing rule states that vehicles can only overtake other vehicles on the left (if there is no congestion). If the speed drops below a certain threshold, the traffic is assumed to be congested and the passing rule no longer holds. The lane usage rule states that vehicles should drive in the rightmost lane if not overtaking.

MOBIL only incorporates lane change decisions based on the operational level of the driving task. While MOBIL uses acceleration to model lane change decisions, it does not actually calculate these accelerations. A car-following model is needed to calculate the accelerations of the target and follower vehicles (Broekman 2017).

Another recent incentive-based model is the **Lane-change Model with Relaxation and Synchronization (LMRS)**. It is described extensively in section 2.2.2.

B.2.4 Artificial intelligence models

In artificial intelligence (AI) models, a computer is programmed in such a way that it can learn from the data it processes, resulting in increasingly better decisions. Within AI models, artificial neural network models and fuzzy logic models are distinguished.

Artificial neural network models are fundamentally different from rule-based and discrete choice models. They are completely data driven. It is possible to pre-specify some network parameters, but there is little control over the model structure. In research, good fits to empirical data were found (de Azevedo 2014).

Fuzzy logic models are based on if-then rules determining when a vehicle will change lanes. This way of modelling allows a more accurate approximation of driver's actual decision process. At the same time this makes these kinds of models extremely complex. (Broekman 2017).

B.3 Integrated models

Integrated models try to describe both the longitudinal and the lateral behaviour, i.e. they integrate a car-following and a lane change behaviour model in one model framework. The advantage of this is that interdependency between the longitudinal and lateral behaviour can be taken into account.

The integrated model developed by (Toledo et al. 2007) (also called the **Toledo model**) is based on three steps: a short-term goal, a short-term plan and the driver's actions. The short-term goal is the specification of the target lane by the driver. The short-term plan is selecting a target gap. The driver's actions are to accelerate or decelerate to reach the target gap and to change lanes. Since the short-term goal and the short-term plan cannot be physically observed they are called 'latent behaviour'. Since driver decisions have an effect on the next goal and plan through appropriate specification of the choice probabilities, there is interdependency between the different steps. Moreover, it is assumed that only one lane change can be performed in a time step, which is realistic since the time interval between steps is usually very small. The Toledo model uses part of Ahmed sub-models. Lane changes are modelled by a discrete function while the car-following behaviour is modelled by a continuous function.

The Toledo model has a large number of parameters that can complicate implementation of new features and calibration of the model afterwards (Broekman 2017). It can have difficulty adapting to different scenarios. Moreover, it includes a trade-off between mandatory and discretionary lane changes by combining the lane change model with incentives (Schakel et al. 2012).

The number of integrated models is much smaller than the number of longitudinal and lateral behaviour models. Although some of the longitudinal or lateral models achieve a limited amount of integration with the other kind, these cannot fully take into account the interdependencies between longitudinal and lateral behaviour that exist in reality. The Toledo integrated model on the other hand does achieve this. Another advantage of this model is that it takes interdependency between chronological decisions into account, which is not achieved by most non-integrated models. However, using the Toledo model in simulation can be very complicated since it has such a large number of parameters, severely complicating validation and calibration, as was shown in earlier research.

Appendix C

Traffic simulation platforms

This appendix gives a more detailed description of the traffic simulation platforms that have been considered for this study. Special attention is paid to the possibilities of extending the models and to related applications in simulation studies.

C.1 VISSIM

VISSIM is a microscopic traffic simulator (modelling the behaviour of individual vehicle units) developed by PTV and has integrated a psycho-physical car-following model, which is the Wiedemann model and a lane change model based on route following, desired speed and a 'time to collision' indicator. It incorporates stochastic vehicle behaviour. It is widely used for urban as well as motorway studies and is able to model all kinds of motorway networks as well as complex intersections in urban areas and all kinds of traffic modes (e.g. cars, trucks, trams, buses, bicycles and pedestrians) (Deng 2016, Oud 2016, Broekman 2017).

VISSIM's lane change model considers three elements according to (Oud 2016):

- Lane selection: a vehicle checks whether a mandatory lane change is necessary in order to follow its desired route. At a certain distance from the decision point, the driver becomes aware of the need to change lanes and attempts a lane change. Before executing the lane change, the possibilities are considered using a gap acceptance theory based on 'time to collision'. If a mandatory lane change is not necessary, it is checked whether a discretionary lane change can be executed. For this the driving conditions of the current lane and the adjacent lanes are compared in terms of speed, route following and 'time to collision' and the lane with the best conditions is chosen. Random lane changes do not exist in VISSIM.
- Lane change: the desirability of changing lanes is determined. Similar as in FOSim, the required deceleration of the vehicle and the follower in the target lane are considered. The maximum acceptable deceleration is determined by the necessity to change lanes, i.e. by the proximity of the decision point. If a vehicle comes too close to the decision point without being in the desired lane, it will make an emergency stop. Driver's aggressiveness will increase as they get closer to the decision point.
- Overtaking regardless of lanes: a unique element of VISSIM is that vehicles can detect if they can physically move laterally to overtake another vehicle regardless of lanes. If there is enough space, a vehicle might overtake another vehicle. This feature is not important for motorway simulation since vehicles will then always use another lane for overtaking.

Moreover, there are several important parameters that can be set that determine the vehicle behaviour in simulation (Oud 2016):

- Waiting time before diffusion: the maximum time of a vehicle at the emergency stop position before it is removed from simulation.
- Minimum front or rear gap: the minimum distance gap with the leading and following vehicles on the target lane that must be there to be able to execute a lane change at standstill.
- Collision time value: the minimum time gap with the leading vehicle in the adjacent right lane to decide if the vehicle should change lanes to the right because of the 'keep right' rule.
- Safety distance reduction factor: the reduction factor applied to the safety distance (i.e. desired gap) during a lane change. Upon completion of the lane change, the original safety distance is reapplied.
- Maximum deceleration for cooperative braking: the maximum deceleration of a vehicle in case of cooperative braking, i.e. braking to allow a lane change of another vehicle into the vehicle's lane.

Gap acceptance values can be defined for different locations in the network and a practically unlimited number of vehicle types can be added. All these vehicle types have their own vehicle length, maximum speed and maximum acceleration/deceleration. More than 50 behavioural parameters can be set for the car-following and lane change behaviour. This can make calibration and validation of this model hard. In VISSIM, the critical gap becomes shorter along the on-ramp to model the growing urge to merge as one gets further along the acceleration lane (Daamen et al. 2010).

Advantages of VISSIM are that it is easily available at Delft University of Technology and offers a huge flexibility by allowing for implementing external driving behaviour, the possibility of adding many vehicle classes and setting many behavioural parameters to fit the needs of the user.

A disadvantage of VISSIM is that a lot of functions remain hidden for the user. This makes it less attractive to use as simulation platform since it can be unclear whether the modelling is realistic. Moreover, the large number of parameters make it hard to calibrate the model. Another disadvantage is that it typically overestimates the number of discretionary lane changes.

C.1.1 Model alterations

VISSIM has a COM server interface that shares the internal vehicle states of objects during simulation so that users can access and modify vehicle driving behaviour.

A classic traffic simulator cannot simulate operations of ACC and CACC. In (Liang et al. 2015) VISSIM was used to simulate CACC vehicles using a C++ DLL (Dynamic Link Library) plug-in. This DLL file works as an External Driver Behaviour Model (EDBM). It can determine the next step manoeuvre: acceleration/deceleration, lane change, vehicles location and vehicles trajectory.

VISSIM has the option to replace the internal driving behaviour by a fully user-defined behaviour for some or all vehicles. For this it has an External Driver Model DLL interface. The user-defined algorithm is implemented in a DLL that is written in C/C++. The DLL code is called by VISSIM during simulation for each affected vehicle in each simulation time step to determine the behaviour of the vehicle. VISSIM supplies the information on the vehicles' and their surroundings' current state to the DLL. The DLL then computes acceleration/deceleration and lateral behaviour and supplies the update state back to VISSIM.

The external driver model can be activated for each vehicle type separately by checking the checkbox VISSIM/Base data/Vehicle Types/External Driver Model. Optionally a parameter file can be used. The driving behaviour of all vehicles of this vehicle type will then be calculated by the selected DLL. The DLL file should contain specific functions in order to work.

C.1.2 Related applications in simulation studies

In (Oud 2016) it was attempted to validate the car-following and lane change behaviour of VISSIM among others. They are compared with an empirical dataset in free flow conditions. The performance of the models are tested on the desired speed distribution, the merging point distribution, the accepted gap distributions and the lane change distribution. It turns out that the default parameters do not reflect the observed data. Apparently the driver's attitude and the traffic conditions have a large impact on general driver behaviour. In free-flow traffic conditions, Dutch drivers tend to be risk-averse, concluding from the low number of voluntary lane changes and the wide gap acceptance distribution. This behaviour is usually not part of a model's default parameter values, thus calibration is necessary to simulate correctly. It turns out that VISSIM gives better results than FOSim, but overestimates the number of voluntary lane changes in free flow conditions when using the default parameter values. Calibration could not solve this entirely. Courtesy and speed gain related lane changes remain underestimated while lane changes to keep right are over-estimated. Gap acceptance behaviour was not much improved. This research provides ranges for recommended parameter values for Dutch traffic in free flow.

In (Deng 2016) a CACC controller framework was constructed in VISSIM by adding an object model called 'Platoon'. It was designed especially for truck platoons. It only incorporates longitudinal truck platoon driving behaviour. V2V communication is modelled by sharing vehicle state information. This is done by having the preceding truck share its vehicle state information, including speed, acceleration and position with its follower. Based on this information the follower can decide on its acceleration. Communication delay was not modelled in this study for simplicity. Platoon operations are controlled by the platoon leader. This means that the platoon leader decides on the acceleration, deceleration and inter-vehicle distances of the platoon, depending on the traffic scenario and road infrastructure. For example, inter-vehicle distances can be increased near motorway ramps.

The proposed framework is applied to various cases in the research. One of these cases is the application to a two-lane motorway stretch of 3.5 km without any ramp. It includes a 0.5 km warm-up segment and a 3 km simulation segment. The warm-up segment prevents effects of vehicle loading on

the simulation results. In that way the vehicles are able to adjust their speed and vehicle gaps before entering the simulation segment.

The simulation is run 30 times, of which each takes approximately 45 minutes. The first 15 minutes are used for loading traffic and the output is excluded from analysis. The share of trucks is set at 10% and the traffic demand is set to 1600 veh/h/lane. The desired truck speed is set to 90 km/h. The simulations are conducted with different desired speeds for passenger cars: 90, 100 and 110 km/h. The desired speed for passenger cars follows a normal distribution with aforementioned means and each time a standard deviation of 8 km/h. The platoon sizes are limited to a maximum of three due to limited data for the estimation of air drag reduction. The passenger car equivalent (pce) of trucks is set to 4. The CACC parameters are set as aforementioned with an update time interval of 1 s.

C.2 MOTUS

MOTUS (Oud 2016, Broekman 2017) is an open source microscopic simulation tool developed at Delft University of Technology in the Netherlands. It is based on the Lane-Change Model with Relaxation and Synchronization (LMRS), and also includes a car-following model. The car-following model is an adapted version of the Intelligent Driver Model (IDM+). It was developed in the programming language Java and allows expanding the already existent classes and incorporating new features. It has no black boxes, the user has full knowledge and understanding of his actions. Moreover, it allows focusing on specific parts of complex networks during simulation.

The traffic system of MOTUS consists of four elements:

- The network, divided in lane sections and interconnected
- Multiple vehicle classes with optionally an on-board unit such as a navigation system inside vehicles
- Road-side units on a particular lane section
- Controllers that influence specific parts of the system

Since MOTUS is open source, the source code is available to the user. This allows full understanding of the model with all its features. Also, any alterations can be made as wished. Since it was developed at Delft University of Technology, support is relatively easily available. Moreover, MOTUS incorporates the LMRS lane change model, which is a relatively realistic model. The IDM+ car-following model that is used is able to capture shockwave effects well if it is properly calibrated.

The IDM+ car-following model used by MOTUS does not incorporate human reaction time. Also, no thresholds exist to prevent drivers from reacting to every minor change in driving conditions. This is not very realistic. Although the coding in MOTUS is relatively easy, this might decrease its functionality. It also lacks an advanced graphical user interface. Therefore any alterations have to be made by programming.

C.2.1 Related applications in simulation studies

A study by (Broekman 2017) used MOTUS as a simulation platform for implementing and testing the performance of the LMRS model and the Toledo model of simulating driving behaviour around ramps. Research namely indicated that current software models do not simulate this behaviour realistically enough, especially with regard to the lane change behaviour. The simulation results were compared with empirical data. It turned out that the number of discretionary lane changes over the network as well as the spread of mandatory lane changes on the ramps are underestimated by the LMRS. Also, no preparation behaviour before the ramps is visible. The time gap distribution also shows more discrete behaviour than the empirical data. Finally, after validation and calibration, it is concluded that the LMRS model needs to simulate more stochastic behaviour, e.g. by assigning model parameters to a driver from a distribution or by increasing the number of simulated lane changes. Moreover, it is concluded that redetermining the desired speed distribution could lead to more lane changes to gain speed and increase the number of discretionary lane changes.

C.3 Open Traffic Simulator (OTS)

Open Traffic Simulator (OTS) (Broekman 2017) is also an open source microscopic traffic simulation tool developed at Delft University of Technology in the Netherlands. It can be seen as an evolution of

MOTUS, which is its predecessor. It was also developed in Java. OTS contains the same car-following and lane change model as MOTUS.

Similar to MOTUS, adaptations and extensions of the intrinsic models are made possible as the entire underlying framework is easily accessible and there are thus no black boxes.

The same disadvantages of the incorporated car-following model apply as for MOTUS. A main disadvantage of OTS is that it is still partially under construction, making it hard to work with. Moreover, because of this no existent networks are available that can be used for this thesis.

Programming in OTS is more complex than in MOTUS, therefore programming in OTS requires more programming skills. However, in return its functionality is increased, possibly resulting in more accurate simulation results. The same advantages of the incorporated car-following and lane change models apply as for MOTUS.

C.4 AIMSUN

AIMSUN (Oud 2016, Broekman 2017) has both a microscopic and a mesoscopic simulator. The mesoscopic simulator is a unique feature in traffic simulation software tool functionality. The mesoscopic model only calculates the points in time at which a vehicle enters or leaves a road section, while the microscopic model collects all data of vehicles at every time step. The mesoscopic model can therefore be considered as a simplification of the microscopic model. In a simulation, the main part is modelled mesoscopic while a small area is modelled microscopic. In that way the speed of a large-scale model is combined with the detail level of a microscopic model.

The car-following model of AIMSUN is based on the Gipps car-following model and the lane change model is an enhancement of the Gipps lane change model. The models have the functionality that vehicles can display different behaviour in three different behavioural zones. Vehicles in zones near the decision point can display different behaviour than drivers still far away from the decision point.

In AIMSUN, vehicles cannot overtake at on-ramps, vehicles can only move from the on-ramp onto the motorway. Merging from an on-ramp is considered a mandatory lane change. Another feature of AIMSUN is the patience factor, which is a maximum waiting time allocated to vehicles, a random value assigned according to a distribution. This factor determines how long drivers are willing to wait when searching for a sufficient gap before they accept smaller gaps. According to (Oud 2016), there are no mathematical explanations in the manual about this and some other features of the tool.

AIMSUN does not allow overtaking on an on-ramp, which is desirable and realistic. Moreover, the inclusion of a stochastic patience factors allows for heterogeneous driving behaviour with respect to driver aggressiveness. It is uncertain whether AIMSUN is freely available for this research, since it is a commercial product. Also, the algorithms used remain unexplained and therefore AIMSUN is somewhat of a black box.

To what extent alterations to the intrinsic driving behaviour models of AIMSUN are possible remains largely unknown. No explaining literature could be found. In (Huisman 2016) (C)ACC functionality was modelled by adapting some model parameters, which gave plausible results.

C.5 CORSIM

CORSIM (Oud 2016, Broekman 2017) is a microscopic traffic simulation software tool developed by the Federal Highway Authority (FHWA), the American road authority. It consists of two sub-models: NETSIM for urban networks and FRESIM for motorways.

FRESIM uses the car-following model by (Zhang et al. 1998) and the lane change model by (Halati et al. 1997). The lane change desire is calculated for each vehicle every time step. To avoid a ping-pong effect, a time threshold of 3 s is defined during which vehicles cannot change lanes if no mandatory lane change is necessary. At on-ramps, a desired free-flow speed is also assigned to vehicles driving on the on-ramp. This speed is based on the average speed in the adjacent lane. This facilitates smooth merging.

CORSIM allows ten different user types that differ in behavioural parameters, such as minimum and desired gap. Moreover, global gap acceptance parameters differ for each type of lane change and are assigned to each user type. The gap acceptance of individual drivers is determined by the required deceleration of the vehicle to avoid a collision with the leading vehicle in the target lane.

CORSIM prevents a ping-pong effect of lane changes by introducing the 3 s time threshold. It also ensures smooth merging from on-ramps by adjusting the desired speed of the merging vehicle to the speeds in the adjacent lane.

Due to the fact that CORSIM is an American tool and has thus been calibrated for the American situation, the model may in some cases not be able to model the European motorway situation very well. For instance, the 'keep right' rule is not included. This could lead to wrong simulation results when it comes to lane change behaviour in European situations. The limited number of driver classes puts a limitation on the heterogeneity of driving behaviour. Another limitation is that CORSIM does not include the relaxation phenomenon (Oud 2016). It is uncertain whether CORSIM is freely available for this research, since it is a commercial product.

To what extent alterations to the intrinsic driving behaviour models of CORSIM are possible remains largely unknown. No explaining literature could be found.

C.6 FOSim

FOSim (Oud 2016, Broekman 2017) is a microscopic simulation tool developed at Delft University of Technology in the Netherlands in order to model Dutch motorway corridors. Although the latest update of the tool has been published in 2006, the core of the model dates from 1997 and only received small changes since then. It therefore does not incorporate recent insights into lane change behaviour.

The driving behaviour in FOSim is determined as follows according to (Oud 2016):

- Each driver has a desired speed (dependent on the road)
- If the desired speed is not yet achieved, the driver will try to change lanes in order to be able to accelerate.
- If changing lanes is not possible, the driver will adjust his speed and follow the leading vehicle with a desired time gap.
- Drivers will change lanes if this is necessary to be able to maintain their desired route.
- Drivers have a preference for the rightmost lane if no other conditions and limitations apply.

Moreover, in FOSim, lane change desire is based on the following factors according to (Oud 2016):

- Route following: vehicles must follow their desired route.
- Physical limits: lane drops, accidents and other physical obstructions imply mandatory lane changes.
- Acceleration and speed of the leading vehicle: if the leading vehicle has a speed that approximates the desired speed of its follower or accelerates to such an extent that overtaking by the follower cannot be done quickly enough, the follower will not change lanes.
- The required deceleration and that of its follower on the target lane: to avoid a collision with the leading vehicle in the target lane if a lane change is executed, a maximum value of deceleration that is acceptable for the vehicle and its follower in the target lane is taken into account.

At on-ramps the maximum deceleration that a vehicle accepts increases linearly from zero at the beginning of the acceleration lane to the maximum value at the end. This ensures that a sufficient gap will always appear at some point and thus that vehicles will always be able to merge if the maximum deceleration chosen is high enough.

FOSim is easily available for students at the TU Delft and has been designed and calibrated for Dutch motorways. It has a straightforward user interface that helps the user to easily adapt all kinds of simulation variables. It can generate all kinds of output that can serve as performance indicators. An extensive manual and even a basic FOSim course is available to get acquainted with the model.

According to (Oud 2016) FOSim does not have probabilistic distributions of driver characteristics. Many parameters, such as desired speed and maximum acceleration are fixed or can only be set within very limited boundaries. This makes the model less suitable for relatively small scale use such as at an on-ramp. Also, only five different vehicle types can be defined, of which three car types and two HDV types.

It is possible to program new functions in FOSim, but no documentation is available on how this could be done. Adjusting vehicle type parameters is a possibility to mimic platoon behaviour, although in that case no communication between the vehicles is modelled.

C.6.1 Related applications in simulation studies

FOSim is used by (Kolen 2013) to evaluate the performance of the model in terms of vehicle merging behaviour by comparing to an empirical data set. It was found that in FOSim, vehicles merge much earlier. The number of lane changes however was comparable as well as the average speed per lane during free flow. During congestion the average speed per lane was a lot different. In FOSim, there seems to be no interaction between the lanes, indicating that the gap acceptance model is not simulating accurately. Especially the location of the merge is a lot different than that in the empirical dataset.

In (Oud 2016) it is attempted to validate and calibrate the car-following and lane change behaviour of FOSim among others. They are compared with an empirical dataset in free flow conditions. The performance of the models are tested on the desired speed distribution, the merging point distribution, the accepted gap distributions and the lane change distribution. It turns out that the default parameters do not reflect the observed data. Apparently the driver's attitude and the traffic conditions have a large impact on general driver behaviour. In free-flow traffic conditions, Dutch drivers tend to be risk-averse, concluding from the low number of voluntary lane changes and the wide gap acceptance distribution. This behaviour is usually not part of a model's default parameter values, thus calibration is necessary to simulate correctly. A main issue is that FOSim is too deterministic regarding driver characteristics. Implementation of probabilistic behaviour is possible and would require programming, but this was outside the scope of this research.

C.7 MITSIMLab

MITSIMLab (Broekman 2017) is an open source microscopic traffic simulation software tool that runs on the Linux operating system. The car-following model is based on the Ahmed model and the lane change model is based on the Choudhury and Toledo model. It consists of three components: Microscopic Traffic Simulator (MITSIM), Traffic Management Simulator (TMS) and the Graphical User Interface (GUI). MITSIM is the actual traffic simulator while the TMS defines the traffic control measures applied in the simulation. The GUI visualizes the simulation with an animation.

Since MITSIMLab is open source, it is freely available for download. The open source nature of MITSIMLab also allows full understanding of the model as all components can be viewed. The GUI is extensive and has detailed vehicle animation. The source code can be modified as wished in the programming language C++.

MITSIMLab is mainly applied to evaluate the effects of traffic control measures and is less appropriate if no such measures are present, such as in the motorway situation of this research. Moreover, it runs on Linux OS and no system running on Linux is available for this research. The lane change model used also limits the validity of the merging behaviour that will be displayed and its effects on traffic flow.

C.8 MATLAB applications

MATLAB (MathWorks 2015) is a high-level programming language software tool that allows multiple tasks such as the manipulation of data and the implementation of algorithms. An important feature is the function, which is a group of statements that can perform a certain task. They can deal with various variables and can return one or more arguments. Several codes that are programmed in MATLAB exist that can be used as a simulation framework of motorway traffic around merging areas.

MATLAB is available for students free of charges. The built-in functions provided with the software are explained thoroughly in the manual. Moreover, MATLAB is very flexible as for example any car-following and lane change model can be programmed in the form of functions. Changing the driver behaviour is possible by adjusting the relevant parameters, e.g. acceleration rate and gap to change the degree of aggressiveness. Another advantage of MATLAB is that it is designed to interact with other software and can for example read worksheets of MS Office Excel by using a certain function. Programming should be relatively easy since MATLAB was designed to be accessible. Although

MATLAB provides a lot of flexibility, no full microscopic traffic simulation functionality exists. The functionality of the available codes is limited.

Any model alterations can easily be done by altering the code. Since MATLAB programming is easier than most other programming languages, any alterations can be made relatively easy. Performance indicators can be obtained as wished by programming the proper equations and corresponding visualizations.

C.8.1 Related applications in simulation studies

In (Ntaflos 2017) MATLAB was used as simulation software. For this research two codes were used and adapted.

The first code is a simulation framework for the simulation of motorway traffic around merging areas. It is a sequence of different functions. There is a main function that includes a main loop from which the other functions are called. The code generates vehicles and lets them propagate through the simulated environment every time step. The vehicles are programmed in such a way that they are considered to be driven by human drivers, i.e. manually. The simulation environment is a two lane motorway. This first code was developed by Wouter Schakel of Delft University of Technology.

The second code is an extension of the first. It implements ACC and CACC equipped vehicles. This code also allows vehicle to infrastructure communication by letting the equipped vehicles communicate with a road side unit. This code was used to evaluate the impacts of a communication based merging assistant system on traffic flow efficiency. The simulation environment is a one lane motorway, which prohibits studying the impact of a certain strategy on lane change behaviour.

Both codes use MOBIL as a lateral driver behaviour model. The car-following model used is IDM. The ACC and CACC vehicles obviously have their own algorithms for longitudinal movement.

During simulation collisions occurred and adjustments to the codes were made to improve driving behaviour. This however could not prevent all collisions from happening, although a more realistic lane change pattern was observed, in which vehicles change lanes only if the gained benefit is large enough.

C.9 Overview of integrated driving behaviour models

A summarizing overview of the car-following and lane change models used by each of the described simulation platforms is given in Table C.1.

Table C.1: Integrated car-following models and lane change models of the different traffic simulation software platforms.

Platform / model	Car-following model	Lane change model
VISSIM	(Wiedemann 1991)	Based on speed, route following and 'time to collision' (Sparmann 1978, Willmann 1978)
MOTUS	IDM+	LMRS
OTS	IDM+	LMRS
AIMSUN	Gipps	Enhancement of Gipps (Barceló and Casas 2005)
CORSIM	(Zhang et al. 1998)	Gap acceptance based on 'collision avoidance', no relaxation (Halati et al. 1997)
FOSim	Based on desired speed and time gap	Based on route following, physical limits, acceleration and speed of leading vehicle and maximum deceleration
MITSIMLab	(Ahmed 1999)	(Choudhury 2007, Toledo et al. 2007)
MATLAB applications	IDM	MOBIL

C.10 Other simulation tools

Apart from the simulation tools compared, many other simulation tools exist (Ni 2017, University of Leeds 2017). These have been left out of the comparison because they are regarded as unsuitable for various reasons.

- **HUTSIM**: urban traffic simulation and control tool by the University of Helsinki.
- **PARAMICS**: complete urban and motorway network simulation tool originally developed by the Edinburgh Parallel Computing Centre at the University of Edinburgh and SIAS Ltd. It has subsequently been further developed and marketed by both Quadstone Ltd and SIAS Ltd.
- **MicroSim**: microscopic simulation tool developed at the University of Cologne.
- **SimTraffic**: microscopic simulation tool developed by Trafficware.
- **TexSIM**: microscopic simulation tool developed by the Texas Transportation Institute to help in the design of real-time traffic control systems.
- **SMARTAHS** and **SMARTPATH**: micro-simulation tools developed as part of the PATH program at the University of California, Berkeley.
- **TRITRAM**: traffic simulation tool developed by CSIRO and the Roads and Traffic Authority of New South Wales, Australia.
- **PADSIM**: traffic control tool developed at Nottingham Trent University Computing Department.
- **SHIVA**: microscopic simulation tool for testing intelligent vehicle algorithms.
- **HIPERTRANS**: a European Commission DGVII funded project to develop a micro-simulator linked to an adaptive signal control system.
- **PLANSIM-T**: microscopic simulation tool developed at the University of Cologne.
- **PELOPS**: sub-microscopic simulation tool developed at the Institut für Kraftfahrwesen Aachen, Germany.
- **TRANSSIMS**: A US Department of Transportation funded micro-simulation tool developed by the Los Alamos National Laboratory.

Appendix D

Explanation and validation of the implemented driving behaviour in MOTUS

In this appendix, an elaborate explanation of MOTUS and the adaptations and extensions to MOTUS are given in sections D.1 and D.2 respectively. The modifications are validated in section D.3.

D.1 Description of MOTUS

Before the adaptations to the vehicle driving behaviour as implemented in MOTUS are explained, first a more detailed description of the basic structure of MOTUS is given in section D.1.1 as well as brief explanations of how the necessary model objects are created in section D.1.2 and how the functionality of the model is extended in section D.1.3.

D.1.1 Basic structure of MOTUS

As mentioned in **Appendix C**, MOTUS is open source and programmed in Java. The simulated traffic system can be seen as a set of interacting objects. These can either be physical (e.g. road, vehicle and driver) or virtual objects (e.g. vehicle trajectories). The objects are connected in a top-down structure as shown in Figure D.1.

Each object represents a Java class that contains methods and attributes that define the characteristics and behaviour of the object. The connection lines show the defined links between the different classes. These relations between the classes allow getting information from other connected classes in a top-down direction. For example, to find the trajectory of a specific vehicle, the correct vehicle can be called from the vehicle class. The dashed connection lines show the defined inheritance links between classes, where a class extends the functionality of another class. For example, a detector is a type of road side unit (RSU).

Moreover, the so-called abstract classes cannot have objects (also called instances) of that class in the traffic system. However, using inheritance their functionality is a part of the subclass(es) that extend these abstract classes. For example, there are no 'jMovable' objects in the traffic system, but the attributes of this class are used by the 'jVehicle' objects (the vehicles) in the traffic system. Finally, the classes that are not connected are so-called utility classes.

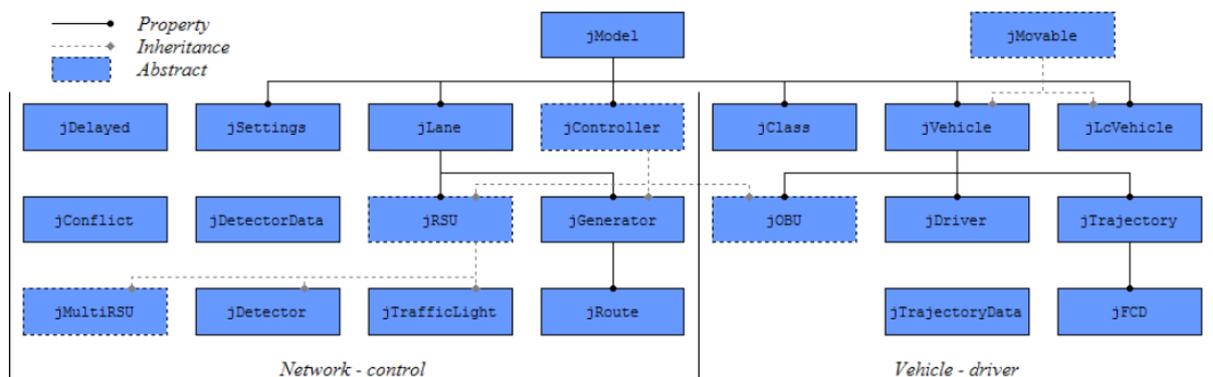


Figure D.1: Basic structure of MOTUS (TU Delft 2017).

All objects have a functionality that is invoked using their methods. During a simulation, all desired methods are invoked in a cascading way. First the 'jModel.run' method is invoked. It calls the 'run()' method of all RSUs, OBUs, controllers and generators in that order. After that the 'jDriver.driver()' method is invoked on all drivers. Lastly, the vehicles are moved with the

'jVehicle.move()' method and then the model is prepared for the next time step. This is repeated until the model has been performed for all given time steps.

There are several important features of MOTUS that affect traffic operations. During a lane change, there is a temporary virtual place-holder vehicle in the target lane. Moreover, vehicles can only move along lanes and are moved by defining their acceleration. Important for this research is that lane changes are never enforced or blocked. Vehicles that can no longer follow their route or exceed a dead-end lane are deleted and a warning message is given (TU Delft 2017).

MOTUS comes with a graphical user interface (GUI) (not shown in the figure) that supports basic functionality. It can visualize a simulation run in which the network and vehicles are shown in a 2D aerial view. The simulation speed can be controlled and several vehicle characteristics such as speed, desired headway and vehicle class ID can be visualized with vehicle colour indications. User-defined additional graphics can be implemented as well.

D.1.2 Creating the model objects

Before the model can be used, all desired model objects need to be created. This is done in a script in Matlab. In this script, the objects are created in a top-down order according to the scheme of Figure D.1. First a 'jModel' object is created in which general settings such as the time step and the simulation period can be set. Next, the network is created by defining lane sections ('jLane' objects) and connecting them where relevant. The end of the lanes that are a destination have a destination number. Then 'jGenerator' objects are created, which generate the vehicles. They are connected to a specific lane. They have a set of 'jRoute' objects, which are the routes to choose from, the route probabilities, as well as a set of class probabilities, which define the probabilities of vehicle-driver classes. The traffic demand is also set here. RSUs are also created at this point. In this case this means that loop detectors are placed on the lanes. Next, the vehicle-driver classes are created by defining 'jClass' objects. In order to do so, a vehicle with driver needs to be created first by creating a 'jVehicle' object and then a 'jDriver' object. Several behavioural parameters are set in it. Stochastic vehicle and driver parameters can be set with parametric distributions. The last step before the model can be run is initialization. The simulation can be visualized by creating an object of the GUI. Simulation output data is generated by saving detector data and trajectory data. This data can later be loaded in Matlab for analysis.

D.1.3 Extending the model functionality

To be able to extend the model functionality, a program in which Java classes can be created and edited is necessary. For this, the integrated development environment (IDE) Netbeans (Sun 2017) is used, in which MOTUS was developed.

The proposed (C)ACC controller is implemented in MOTUS by creating a Java subclass in a new package called 'jPlatoonDriver' that is an extension of its superclass 'jDriver'. In that way the new class inherits all the attributes and methods of the superclass. The superclass contains the default vehicle driving behaviour. The new subclass overrides the default driving behaviour of its superclass where desired by overriding methods and attributes. This should be done with caution as MOTUS was designed as a research tool that can be extended with new functionalities. This means many methods and attributes are accessible, allowing more damage to the default model than with other software tools. When new code shows unintended behaviour, this could corrupt the default model.

D.2 Automated driving model implementation

A full explanation of the implemented automated driving behaviour for truck platoons and the adapted human driving behaviour caused by behavioural adaptations is given in section D.2.1 and D.2.2 respectively. A description of additional adaptations made to the vehicles' characteristics and to the model output is provided in section D.2.3.

D.2.1 Automated driving for truck platoons

In the simulations, the equipped trucks have to satisfy some conditions before they are allowed to form a platoon. Moreover, there are certain manoeuvres that they are not allowed to make when platooning, as explained in the next sections.

Platooning conditions

For calculating the acceleration used for longitudinal driving, the (C)ACC controller will be used if the considered vehicle is an equipped truck. In case there is no preceding vehicle (or the preceding vehicle is out of the considered range), the equipped trucks will use cruise control. If there is a preceding vehicle, it is first checked if the predecessor is also an equipped truck and whether it is close enough to attempt platoon formation. Thereby an equipped predecessor is considered close enough if the inter-vehicle time gap is equal to or smaller than the desired equilibrium gap of CACC excluding the standstill distance multiplied by ten, plus the standstill distance: $s_0 + 10 * v * t_{des}$. In this way platoon formation is only initiated if the predecessor is within the sensor range and if the estimated time it takes to complete a formation manoeuvre is acceptable, i.e. no more than a few minutes. If the predecessor is out of this range, the considered vehicle will apply the ACC controller.

If the predecessor is within this range, it will first be checked whether the maximum number of trucks in the platoon (maximum platoon size) will not be exceeded if the considered vehicle would join the platoon. This is done by checking the status of the predecessor of the predecessor (on the same lane) and so forth. The number of predecessors of which the status is checked depends on the maximum platoon size. The status that is checked contains the vehicle class ID, the gap with the predecessor and the vehicle speed. To determine whether platooning is allowed, at least one of the following conditions should apply, depending on the maximum platoon size:

- The predecessor of the predecessor (...of the predecessor...etc.) is NOT an equipped truck (consider more predecessors as the maximum platoon size increases).
- The gap maintained by the predecessor (...of the predecessor...etc.) with its predecessor should be equal to or larger than the desired equilibrium gap of ACC (consider more predecessors as the maximum platoon size increases).

The second condition ensures that even when there are so many equipped predecessors that the number of equipped trucks in a row exceeds the maximum platoon size, the vehicle in question may still initiate platoon formation with its predecessor if the gap maintained by one of the relevant predecessors is larger than the gap that is maintained when not platooning, i.e. the desired equilibrium gap of ACC. At the same time this condition ensures that the vehicle in question will increase the gap with its predecessor if the gap maintained by one of the relevant predecessors becomes smaller than that desired equilibrium gap.

If platooning would exceed the maximum platoon size, the vehicle in question will use the ACC controller. If not, it will start using the CACC controller with reduced inter-vehicle gap. At this point the considered vehicle will increase its speed to catch up with its equipped predecessor. The catch-up speed is stochastic so that it matches variability in driver behaviour as observed in reality.

Although this speed increase means that the speed limit for trucks will be slightly exceeded, the catch-up manoeuvre is preferred over a slowdown manoeuvre of the potential platoon leader for two reasons. Firstly, it prevents negative effects of truck platooning caused by lower average speeds of trucks. In the future a catch-up manoeuvre might even become legal to prevent these negative effects on traffic flow. Secondly, since the platooning conditions only consider downstream vehicles and given time constraints, it is more convenient to program a catch-up speed that also considers the predecessor rather than having to define additional logic to identify the motives of a follower. Besides these reasons, it is also not expected that this choice has an impact on merging problems at the on-ramp since platoon formation will already be completed before reaching the on-ramp.

When the (C)ACC controller is applied, the maximum acceleration is bound by reaching the desired velocity and vehicle capabilities. This means that cruise control will be applied if it returns a smaller acceleration than the (C)ACC controller and that the acceleration can never be lower or higher than the maximum braking and acceleration capability of the vehicle respectively. The latter was added

as an extension to the model, because MOTUS does not include a maximum acceleration by default, since the nature of the IDM+ already ensures a maximum.

Synchronization

Once the desired acceleration has been calculated, vehicles would normally scan the surrounding vehicles to evaluate whether they need to synchronize to create a gap for another vehicle that is indicating towards this lane. In the case that an equipped truck is platooning, this functionality is turned off. This means that a platooning truck will never yield for a merging vehicle. The platoon will thus never be disengaged on the initiative of one of the platoon members. This is a design choice that was made. It ensures that merging within a platoon is only performed when a vehicle is out of options. This allows better analysis of the effects of platooning at an on-ramp with forced lane changes on traffic performance and efficiency, since the effects of platooning will be larger and thus better noticeable. Moreover, it is also desirable as one would not want a platoon to disengage at every on-ramp.

At the same time vehicles normally evaluate whether to synchronize to change lanes themselves. Again, in the case that an equipped vehicle is platooning, this functionality is turned off. This means that a platooning truck will never synchronize to change lanes. This is because the design choice was made and implemented that platooning trucks will never change lanes. Hence, it also makes no sense to synchronize to change lanes.

An exception to the lack of synchronization of truck platoons can be made by turning this functionality back on. However, this will only be done if simulation results indicate significant merging problems without synchronization.

D.2.2 Behavioural adaptation

The merging behaviour of human drivers is adapted on the basis of the empirical evidence of section 2.3, which implicates some behavioural adaptation in the presence of non-automated truck platoons. The most important adaptation is that merging vehicles tend to accept a smaller inter-vehicle gap when merging in a lane with a truck platoon. Although the empirical evidence is for non-automated truck platoons, it could well be that the effect for automated truck platoons is even larger. If merging drivers know they are dealing with an automated truck, they might know that its systems will always intervene to prevent a collision. Therefore merging drivers may even start taking more risk.

Minimum accepted gap

The decision structure for lane changing according to the LMRS as applied by MOTUS is schematized in Figure D.2. MOTUS evaluates gap acceptance based on an estimation of the required deceleration of a vehicle itself and its new follower. Acceptance of smaller gaps than normal when merging within a truck platoon has been implemented in MOTUS by decreasing the minimum acceptable gap that equipped trucks have. This is used by lane changing vehicles to evaluate the safety of a lane change. It is set to a value that ensures that merging vehicles may even accept gaps with the new equipped follower as low as 0.3 s (normally 0.56 s).

At 85 km/h this adapted minimum gap means there is only approximately 7 m (originally about 13 m) between the equipped truck and its new leader. Given the lag in the AD system of the equipped trucks, this means only very little room is left when an emergency braking manoeuvre would take place at that exact moment. However, given the tested stability limit of the calibrated (C)ACC controller (see section 3.3), a gap of 0.3 s should just guarantee collision-free driving.

Although both the default and especially the new value for minimum gap acceptance might seem very small in order to prevent collisions, it must be said that the unwritten rules applied by human drivers when merging can justify this behaviour. First of all, gap acceptance is based on human estimation of distances, which is often hard to do correctly. Whether a gap is acceptable is mainly judged by the possibility to physically fit the vehicle in the gap. Moreover, in practice the desired gap plays a limited role in the merging decision as relaxation takes place after merging (thereby also explaining the hysteresis effect). During congestion accepted gaps may be even smaller since there is simply too little room. Also, human drivers are very good at anticipating, so if they notice

that their anticipated predecessor will have no reason to apply its brakes any time soon, there is little danger in accepting a small gap. Lastly, the limited acceleration power and length of the acceleration lane often more or less force drivers to accept the first gap offered to them, as is also supported by empirical evidence (Vermijs 2017).

In empirical data study by (Daamen et al. 2010), cases in which the gaps between the merging vehicle and the new leader and follower vehicles is less than 0.25 s were observed. In (Schuurman 1991) a similar conclusion on acceptance of extremely small gaps was found, namely that approximately 50% of merging vehicles will accept gaps smaller than 0.5-1.2 s.

As described in section 2.3, gaps maintained and accepted by vehicles are relatively small if there are a lot of non-automated platooning trucks in the same lane. This further justifies the modified minimum gap accepted by other drivers when changing lanes towards a truck platoon.

Concluding, although these small gaps can be considered unsafe from an acceleration capability perspective, they are often found in practice and thus realistic. How much smaller the minimum accepted gap will be when interacting with truck platoons is unknown, but research indicates that a smaller minimum gap is justifiable as it is also observed for interaction with non-automated truck platoons. A conservative limitation to 0.3 s, corresponding to the minimum that still guarantees collision-free driving therefore seems reasonable.

Evaluation of gap acceptance

Normally, MOTUS would make sure that the minimum time gap used to evaluate gap acceptance will never be larger than the current gap. To make sure that the acceptable minimum time gap will not be lower than this predefined minimum acceptable time gap, the method that returns the minimum time gap that is used to evaluate gap acceptance has been slightly adapted. The adaptation ensures that the method can also return a larger minimum time gap than the current time gap. In this way truck platoons will never accept a vehicle merging in front of or within the platoon resulting in a time gap smaller than the predefined minimum time gap. This ensures correct evaluation of gap acceptance even when the CACC time gap is smaller than the predefined minimum time gap.

Although this corrected minimum gap thus helps to correctly evaluate gap acceptance, it will have no effect on the number of vehicles merging within a truck platoon. This is because in all simulation scenarios the inter-vehicle gaps maintained by truck platoons are smaller than the gap needed to safely execute such a lane change. The gap needed would namely be at least $0.3 + 0.56 = 0.86$ s plus the length of the merging vehicle. Merging within a truck platoon would thus always lead to unacceptable decelerations. The corrected minimum gap is therefore not useful for merging within a truck platoon, but it is when merging in front of one, or when merging in front of an equipped truck that is not platooning.

Only the minimum gap of the equipped trucks

As can be concluded from the above, it has been chosen to only modify the minimum gap of the equipped trucks and not that of the merging vehicles itself. This has been done because it is assumed that drivers will not accept a smaller gap with their predecessor when merging in front of an equipped truck. After all, their capabilities have not changed. It makes more sense to assume that the smaller gap will only be applied with its new follower, since the follower's automated systems will always make sure it brakes when necessary.

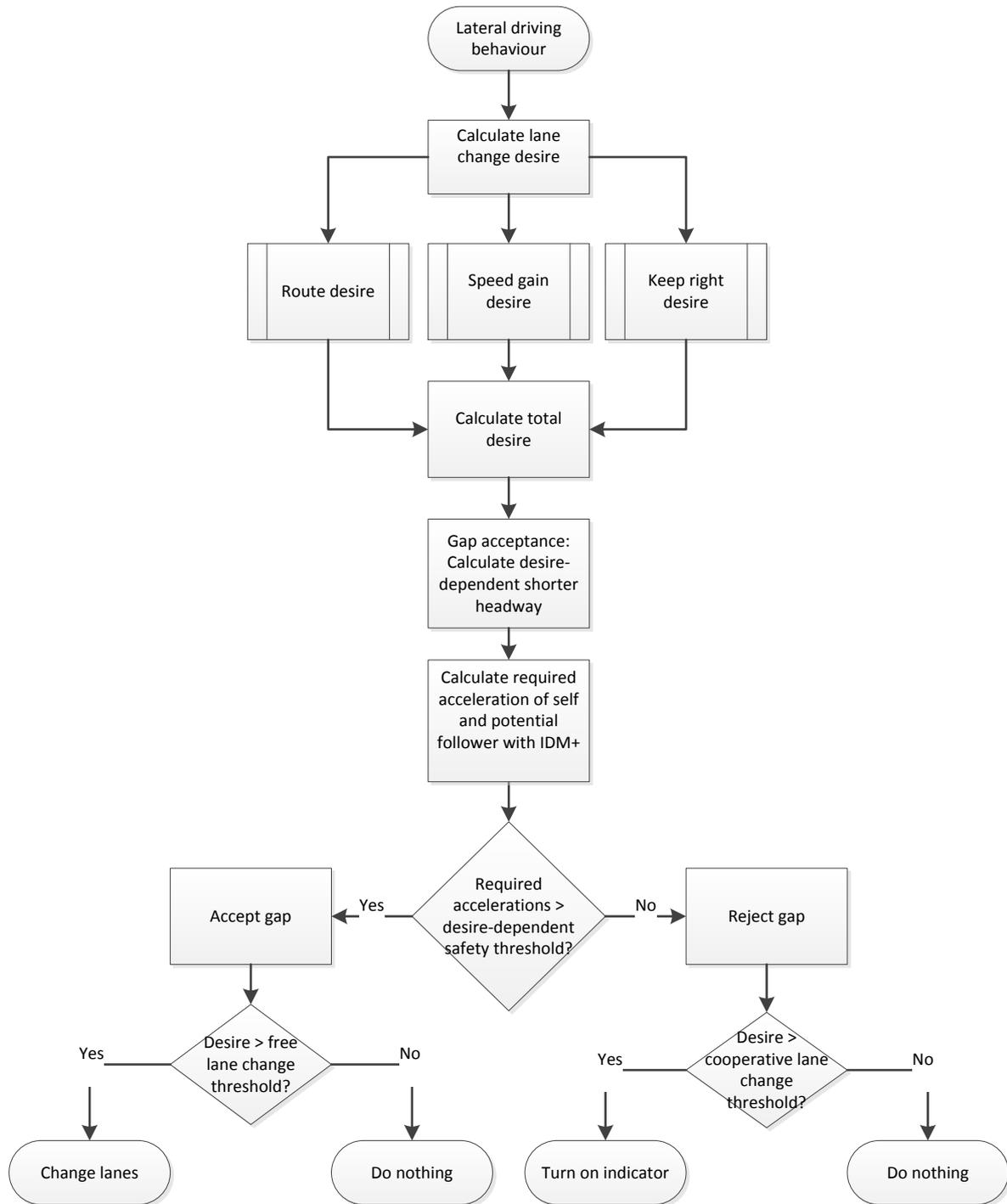


Figure D.2: Flow chart of the lateral driving (lane change) behaviour of LMRS as implemented in MOTUS.

D.2.3 Additional adaptations

In addition to the adaptations to the human merging behaviour, several small other adaptations have been made.

Parameter values

The vehicle lengths of the different vehicle classes implemented have been set to the average lengths as reported by (RDW 2012, Schermers et al. 2014). This kind of heavy truck is by far the

most common type of heavy truck in the Netherlands (RDW 2017). For passenger cars and heavy trucks (the two 'standard' vehicle classes mostly used) these are different from the default values:

- Passenger cars: 4.19 m
- Light trucks: 8.5 m
- Heavy (articulated) trucks: 16.5 m

Furthermore, the maximum deceleration of light trucks has been set to -4.5 m/s^2 , which is lower than for heavy trucks, but higher than for passenger cars and corresponds to the practical value. Similarly, its maximum acceleration has been set to 0.8 m/s^2 to fall in between the other two distinct vehicle classes.

The equipped trucks have a modified minimum acceptable time gap of 0.3 s for aforementioned reasons, while the regular time gap, used to evaluate gap acceptance of itself and others is set equal to the time gap of ACC (1.5 s). This ensures that lane changing is done on the basis of the correct time gap.

Model output

Finally, the Java class that keeps track of all floating car data was adapted to include keeping track of the distance gap and relative speed difference with the predecessor. This additional output allows calculating the time to collision (TTC) (see section 4.3.2) performance indicator for every time step of every vehicle. A vehicle colour indication for the TTC was also added to the GUI to allow visual analysis of this indicator.

D.3 Validation of driving behaviour model parameters

In order to check the validity of the vehicle driving behaviour and traffic dynamics of the simulation model, simulation output is generated that allows analysis of this behaviour and these dynamics. Two base cases are validated: one for the original simulation model with congestion and one without congestion. This allows observing the effects of congestion. Another case that is validated is one for the adapted model with truck platoons (also with congestion). This allows observing the effects of the adaptations as well. The output is obtained from the loop detector data and vehicle trajectories. Twenty random seeds are run for each case for improved reliability of the results. The simulation runs represent one hour of traffic each. A warm-up time of 5 minutes is taken into account. This is equal to the time it takes to fill the network. Loop detector and vehicle trajectory data is only used after the warm-up time has elapsed. The description of the road network used can be found in section 4.1.1.

The parameter values of the (C)ACC controller are according to Table 3.2. The CACC time gap is set at 0.3 s and the maximum platoon size is three trucks. For the congestion cases the traffic intensity is set to 4000 vehicles/h for the motorway to represent a peak period. The on-ramp intensity is initially zero, but is set to 1000 vehicles/h after 15 minutes. A traffic jam will then be created at the acceleration lane. After another 15 minutes, the on-ramp demand is set to zero so that congestion is gradually solved. The share of trucks is set to 20%. The high intensity of section 4.2.3 is used for the no congestion case. The penetration rate of equipped trucks is 100% for the platooning case. Trucks are only generated in the right lane and platoons cannot yield for merging vehicles nor change lanes. IDM+ and LMRS parameter values have retained their standard calibrated values (Schakel et al. 2012) as shown in Table D.1.

Table D.1: Applied vehicle characteristics and human driving model parameter values.

Parameter name	Symbol	Cars	Light trucks	Heavy trucks	Equipped trucks
Vehicle length [m]	l	4.19	8.5	16.5	16.5
Max. vehicle speed [km/h]	v_{Max}	130	85 ± 2.5	85 ± 2.5	85 ± 2.5
Catch up speed [km/h]	$v_{CatchUp}$	-	-	-	90 ± 1

Max. acceleration [m/s²]	<i>a/aMax</i>	1.25	0.8	0.4	0.4
Max. deceleration [m/s²]	<i>aMin</i>	-6	-4.5	-4	-4
Comfortable deceleration [m/s²]	<i>b</i>	2.09	2.09	2.09	2.09
Standstill distance [m]	<i>s0</i>	2	3	3	3
LMRS min. time gap for very desired lane change [s]	<i>Tmin</i>	0.56	0.56	0.56	0.3
Regular car-following gap [s]	<i>Tmax</i>	1.2	1.2	1.5	1.5
Speed limit adherence factor [-]	<i>fSpeed</i>	(123.7/120) ±(12/120)	1	1	1
LMRS free lane change threshold [-]	<i>dFree</i>	0.365	0.365	0.365	0.365
LMRS synchronized lane change threshold [-]	<i>dSync</i>	0.577	0.577	0.577	0.577
LMRS cooperative lane change threshold [-]	<i>dCoop</i>	0.788	0.788	0.788	0.788
LMRS speed gain for full desire [m/s]	<i>vGain</i>	69.6/3.6	69.6/3.6	69.6/3.6	69.6/3.6
LMRS critical speed for a speed gain in the right lane [m/s]	<i>vCong</i>	60/3.6	60/3.6	60/3.6	60/3.6
LMRS safe deceleration for lane changes [m/s²]	<i>bSafe</i>	2.09	2.09	2.09	2.09
LMRS relaxation time [s]	<i>tau</i>	25	25	25	25
LMRS mandatory lane change distance [m]	<i>x0</i>	295	295	295	295
LMRS mandatory lane change time [s]	<i>t0</i>	43	43	43	43

D.3.1 Observed traffic dynamics

In both congestion cases, once the on-ramp intensity is no longer zero, congestion forms at the acceleration lane after a while because of the large number of vehicles merging. This also causes congestion on the acceleration lane. A wide moving jam is formed on the motorway moving upstream. Once the on-ramp demand becomes zero, congestion at the on-ramp area gradually solves and the resulting shockwave moves upstream.

Flow- and speed-contour plots

The traffic pattern is captured in the flow- and speed-contour plots of Figure D.3 (no truck platoons) and Figure D.4 (run with platoons). The wide moving jams can be clearly seen. The

speed with which the jams move upstream can be derived from the angle at which they act. The head and tail of the jam move backward with approximately 20-25 km/h in both cases. Research learns that the shockwave speed of a wide moving jam is approximately equal to 15-20 km/h. The rough estimation of the observed speed thus does not deviate much from this range and hence it is concluded that the model is well able to model the traffic flow dynamics of a wide moving jam realistically. Another observation is that the flows and speeds in the jam are on average much higher in the truck platooning case, so that the impact of the jam is much smaller. This might indicate a capacity increase for the case of truck platooning.

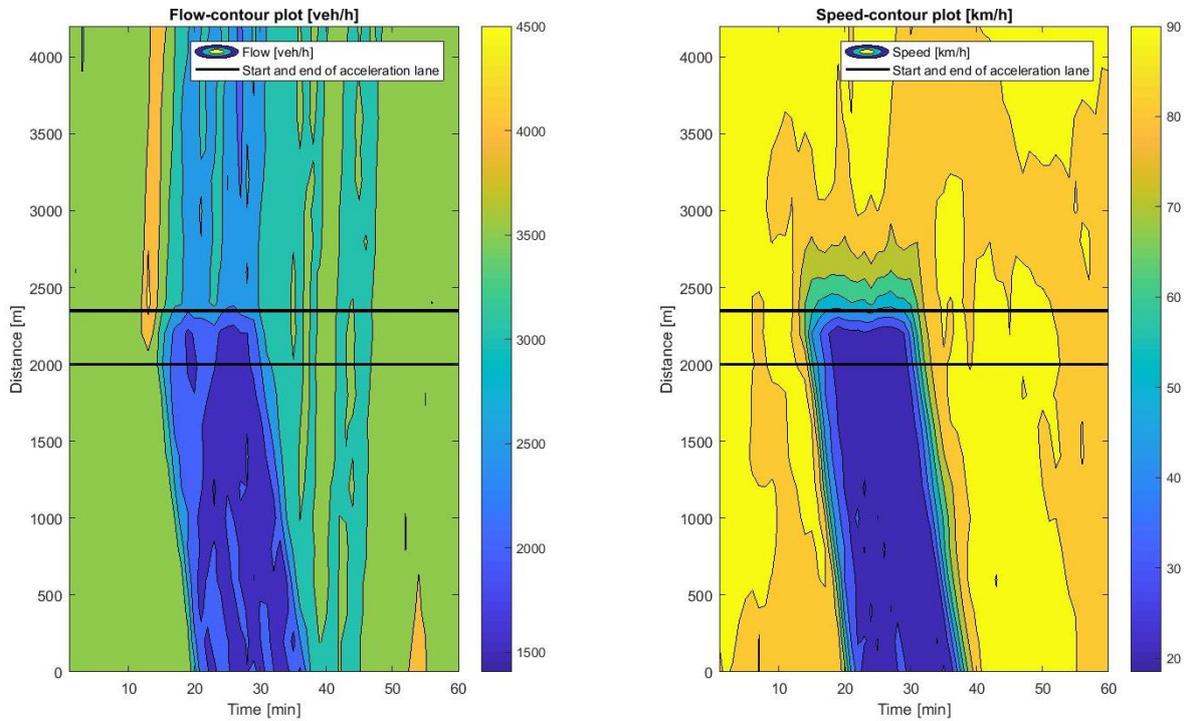


Figure D.3: Flow- and speed-contour plots of the simulation test runs (no truck platoons).

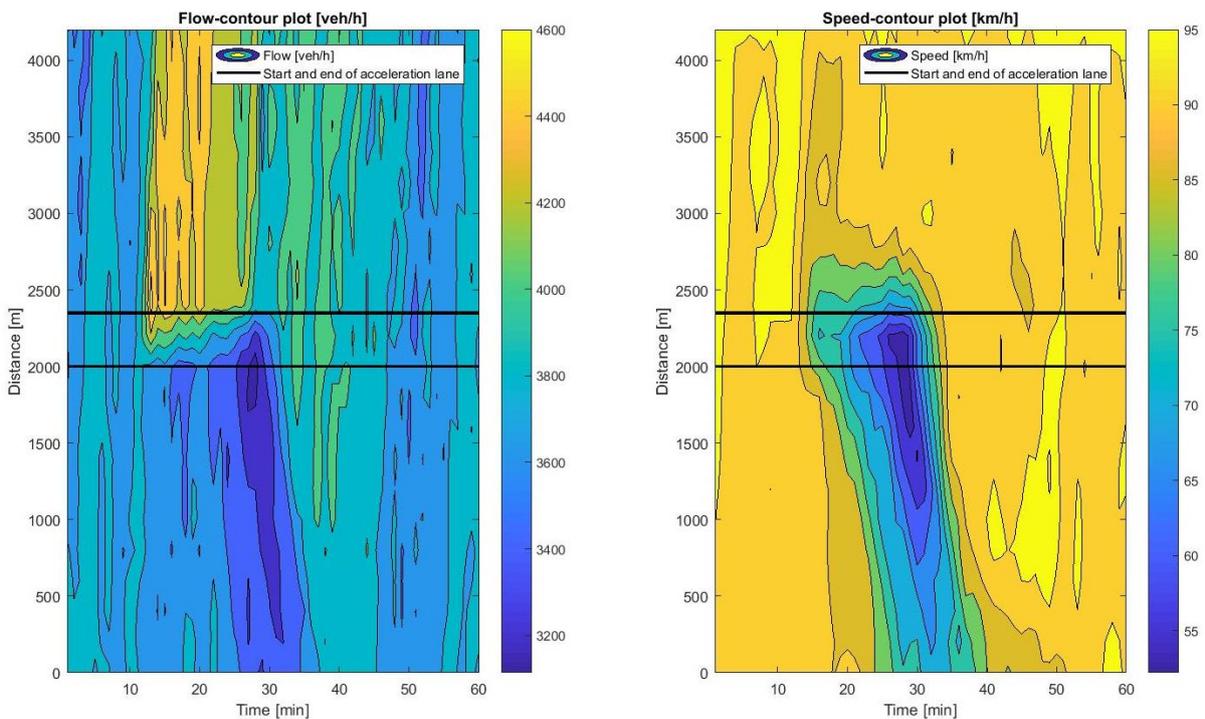


Figure D.4: Flow- and speed-contour plots of the simulation test runs (with truck platoons).

Fundamental diagrams

Traffic dynamics are also visualized in the fundamental diagrams (Figure D.5 and Figure D.6). The free flow branch as well as the congested branch can be clearly distinguished. It can be seen that only data from the detectors at the acceleration lane as well as that from the detectors upstream of the acceleration lane is in the congested branch. This corresponds with the fact that jams move in upstream direction, as can also be seen in the flow-and speed-contour plots.

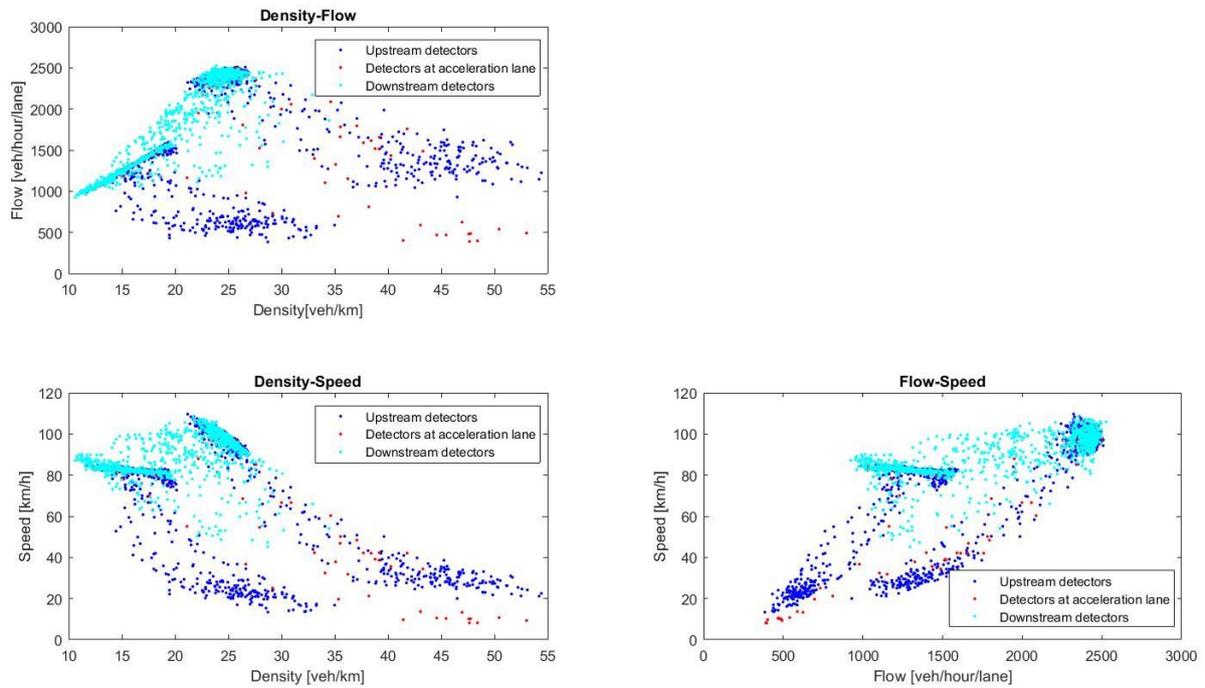


Figure D.5: Fundamental diagrams of the simulation test runs (no truck platoons).

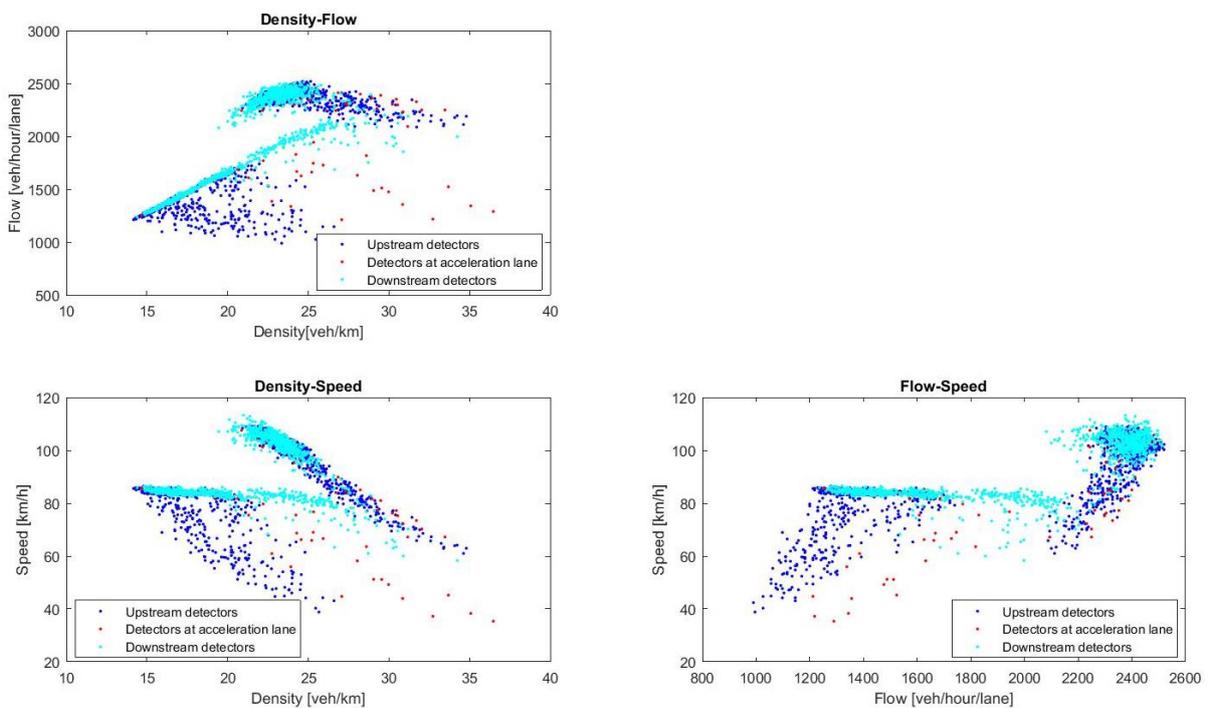


Figure D.6: Fundamental diagrams of the simulation test runs (with truck platoons).

Hysteresis

Other common traffic phenomena shown are the large spread in the congested branch, caused by stochasticity of driver behaviour. These are for instance maintaining different gaps for the same speed as drivers react differently to congestion. When entering or coming out of a congestion, drivers might either react delayed to a change in speed or anticipate a change in speed. This phenomenon is called hysteresis. It can cause a large spread in the fundamental diagram as is indeed observed in this case.

Lane differences

The same detector data is also displayed per lane in Figure D.7 and Figure D.8. This gives insight into the differences between the left and right lane. It can be seen that the average free flow speed in the right lane is approximately 85 km/h in both cases. Given the large share of trucks in the right lane, this makes sense since this is equal to the average speed of the trucks. The observed free flow speeds in the left lane are higher and show a larger spread. This also makes sense since the desired speed of passenger cars is much higher, but the high traffic intensity may lower the average speed and trucks may also be in the left lane. In both cases the congestion level in the right lane is higher. This can be declared by the fact that the right lane has more hinder from the merging vehicles at the on-ramp.

Another phenomenon observed in reality is the convergence of speeds of the lanes with increasing density (Mansvelder et al. 2014). As the road becomes more crowded, the average speed difference between the lanes becomes smaller. In the density-speed plane of the platooning case this convergence is indeed observed for densities between roughly 15-35 vehicles/km. However, for the case without platooning this effect is much less visible. This is because the congestion level is much higher, so that the speed in the right lane deteriorates much faster at higher densities.

Another observation that is also visible in the flow- and speed-contour plots is that the flows and speeds in the jam are on average much higher in the truck platooning case, so that the impact of the jam is much smaller. There is even only little congestion in the left lane. This might indicate a capacity increase for the case of truck platooning.

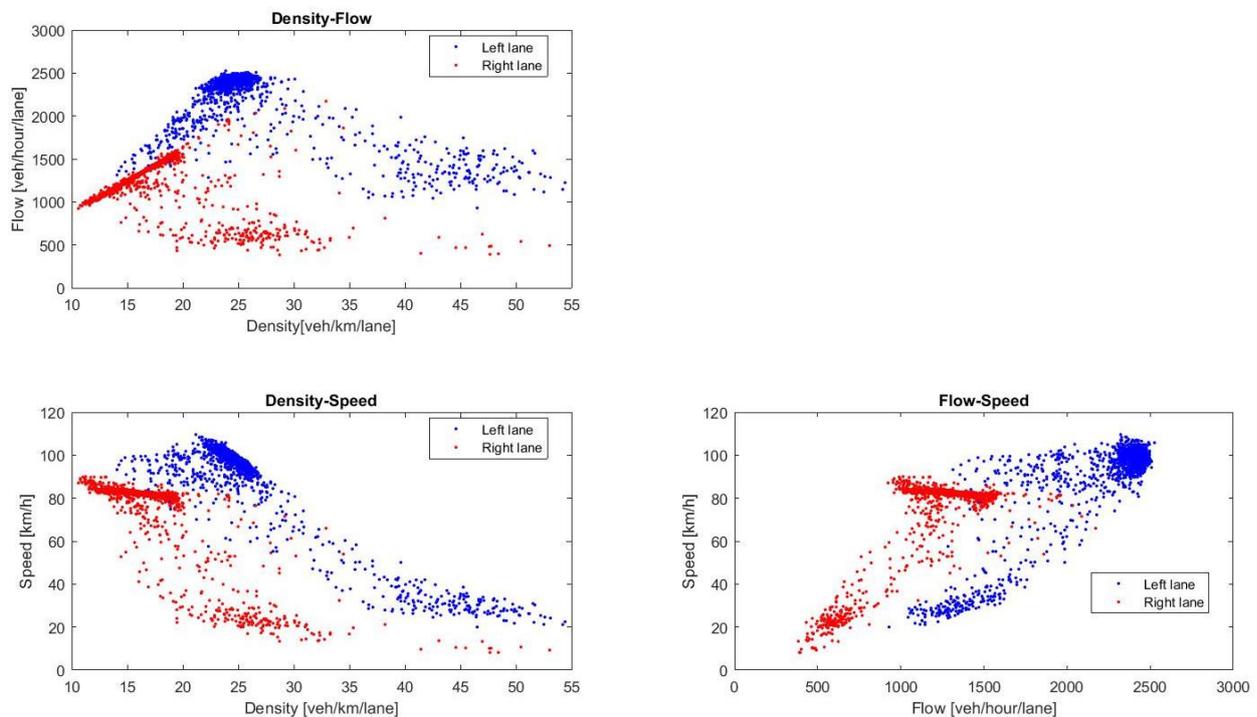


Figure D.7: Fundamental diagrams of the simulation test runs – lane differences (no truck platoons).

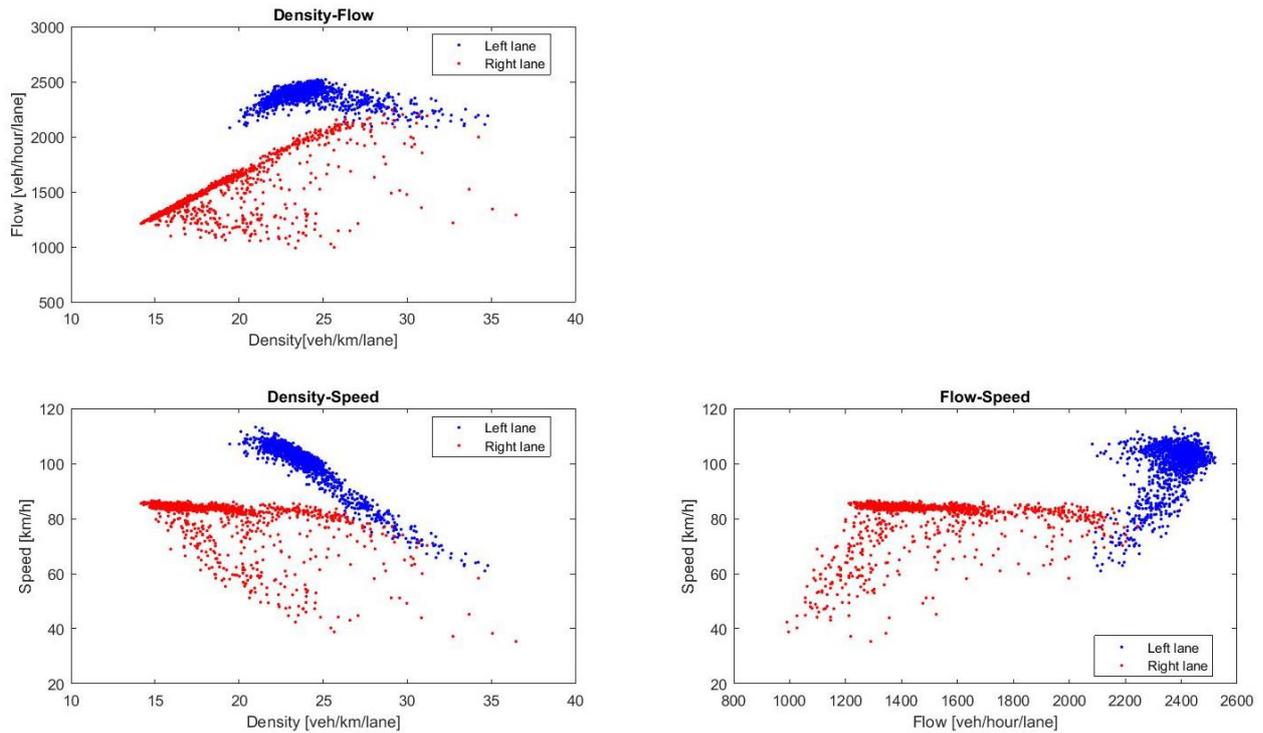


Figure D.8: Fundamental diagrams of the simulation test runs – lane differences (with truck platoons).

Capacity and capacity drop

The data in the density-flow planes shows a maximum free flow capacity of approximately 2500 vehicles/h for the left lane in both cases and approximately 1600 and 2100 vehicles/h for the right lane for the no platooning and platooning case respectively. This gives a total road capacity estimation of approximately 4100 and 4600 vehicles/h for the no platooning and platooning case respectively. For the no platooning case, this corresponds almost exactly to the standard capacity value for a motorway lane section as given in (Henkens and Tamminga 2015) (4128 vehicles/h for 20% trucks). For the platooning case, the capacity found is approximately 11% higher than the standard value. This might be due to the truck platoons since they maintain smaller gaps.

It must be noted though that determining the capacity using the fundamental diagram is very sensitive for the line fitted through the data. Also, the selection of measurements can have a large influence on the capacity value found. Therefore the fundamental diagram method for determining capacity is only useful for a rough indication of capacity, but is unsuitable for calculating capacity (Henkens and Tamminga 2015).

The capacity after congestion (also called queue discharge rate) is typically lower than the free flow capacity. The large spread of the congested branch makes it hard to distinguish such a capacity drop, but when a line is fitted for the data in the congested branch, such a capacity drop is indeed observed for the no platooning case. This confirms the validity of the simulation model. For the platooning case the number of observations in the congested branch is too small to be able to fit a line with acceptable reliability.

Shockwave propagation speed

The slope of the fitted line through the congested data can give an indication of the shockwave propagation speed of the wide moving jam, similar to the speed observed in the speed-contour plot. As mentioned earlier, research learns that the shockwave speed of a wide moving jam is approximately equal to 15-20 km/h. The propagation speed can be estimated from the fundamental diagram using the shockwave **equation** (D.1):

$$W_{ab} = \frac{q_a - q_b}{k_a - k_b} \quad (\text{D.1})$$

Where:

q_a, q_b : flow in free flow and congested conditions [vehicles/h]
 k_a, k_b : density in free flow and congested conditions [vehicles/km]

A shockwave between the free-flow state just before the jam and the congested state within the jam can be considered for this. According to the fundamental diagram of the no platooning case, a free flow speed of 85 km/h corresponds to roughly 12 vehicles/km and 1000 vehicles/h (right lane) or 25 vehicles/km and 2000 vehicles/hour (left lane). Similarly, a congested speed of 30 km/h corresponds to roughly 20 vehicles/km and 700 vehicles/h (right lane) and 45 vehicles/km and 1250 (left lane). Application of the shock wave equation then yields $(1000-700)/(12-20) = -37.5$ km/h (right lane) and $(2000-1250)/(25-45) = -37.5$ km/h (left lane).

The shockwave propagation speeds found using the fundamental diagram are rough estimations because of the large spread in the data. Moreover, the detector data returns the time mean speed (average speed over a period of time), which is always higher than the more correct space mean speed (averages speed on a road section at a fixed point in time). This causes a slight underestimation of the calculated densities, resulting in a higher wave propagation speed than in reality. Moreover, the spread in the congested branch of the fundamental diagram is so large that many possible fitted lines for this branch are possible. It could well be that the actual slope is different than the one assumed here, which will result in a different wave propagation speed. With these limitations in mind, there is no indication that the traffic dynamics in simulation are unrealistic.

Capacity estimation

A more accurate way to estimate the free flow capacity than using the fundamental diagrams is to use the FOSim method (Henkens and Tamminga 2015). This method is used by simulation tool FOSim (see **Appendix C**). The capacity is thereby estimated by taking the highest observed intensity for a time period with congestion as capacity value. The highest value is taken for the period up until the moment at which congestion forms. Research indicates that an aggregation level of five minutes for the measurements is to be preferred as smaller aggregation levels can result in a bias (Henkens and Tamminga 2015). The capacity is measured on a cross-section downstream of the bottleneck (in this case the on-ramp). A detector upstream of the bottleneck is used to determine when congestion has formed. The threshold for congestion is thereby set at 50 km/h. Multiple simulation runs with congestion give a median for the capacity.

Using the FOSim method, the maximum intensity is found to occur right before congestion is formed. It is found to be 4112 vehicles/h on average with a standard deviation of 129 vehicles/h for the no platooning case and 4673 vehicles/h on average with a standard deviation of 77 vehicles/h for the platooning case. This is approximately 0.4% lower and 13.2% higher than the standard capacity value for a motorway lane section as given in (Henkens and Tamminga 2015) (4128 vehicles/h for 20% trucks) respectively. The traffic dynamics displayed by MOTUS thus give a very accurate capacity estimation.

It is noticed by (Henkens and Tamminga 2015) that capacity estimations with the FOSim method are usually between -10 and +10% of the estimation with the Brilon method, which is used to calculate the advisory capacity values used by this source. The capacity estimation with MOTUS falls well within this range. The capacity value found for the no platooning case is thus considered acceptable.

Worth mentioning is that the estimated capacity for the truck platooning case is much higher than for the no platooning case, again indicating an increased capacity due to truck platooning. At the same time the standard deviation is smaller, possibly indicating a decreased sensitivity for disturbances in the traffic stream.

D.3.2 Observed vehicle driving behaviour

The traffic dynamics discussed give an indication of the validity on macro level, but validity on micro level has not been tested yet. To check this validity, we zoom in on individual vehicle driving behaviour. Special attention is paid to the driving behaviour of truck platoons as well as that of merging vehicles.

Although it is not possible to compare the traffic performance and safety in the platooning case with that in reality (because truck platooning is not performed in reality yet), it is possible to compare with traffic situations that are comparable to a certain degree (see also section 2.3). One such situation is a busy motorway freight route where some platooning effects can be observed as the density of trucks at on-ramps is very high. Another situation is the deployment of longer and heavier vehicles on the motorway. The findings from section 2.3 will be used here to evaluate the validity of the observed vehicle driving behaviour in the simulations.

Lane distribution

It is noticed in section 2.3 that with high traffic intensities and many trucks, the left lane will be used more than the right lane. As more vehicles start using the left lane and also more slow vehicles start using it, the average speed in the left lane decreases and more variations in speed occur. The chance of being overtaken on the right also increases. These phenomena are indeed observed in the simulation test runs as can be observed in the fundamental diagrams.

Moreover, the share of vehicles in the right lane decreases when approaching the on-ramp area in reality. In (Schuurman 1991) this reduction was found to be approximately 8%. This is because drivers anticipate merging traffic. This effect is not accounted for in the simulations since vehicles in MOTUS will only change lanes if an effect of the on-ramp is already there. For example, when performing a courtesy lane change for a merging vehicle or when performing a free lane change to be able to maintain the desired speed as the speed in the right lane due to merging vehicles at the on-ramp decreases. This might result in a slight overestimation of the share of vehicles in the right lane, which might result in a slight overestimation of merging problems.

Merging behaviour

The merging behaviour observed in the simulations can also be compared to the possibilities described in section 2.3. Most possibilities indeed occur in the simulation, although not all of them. The LMRS gap search algorithm does not consider vehicles further away than the ones directly surrounding the considered vehicle. This brings with it the limitation that merging vehicles will never accelerate to quickly move to a more downstream gap or brake to move in a more upstream gap. This is a LMRS model limitation that will likely result in an overestimation of the number of vehicles that are not able to merge because there was no acceptable gap.

Merge locations

Literature can also give some clues on the validity of the simulation set-up. Analysis of empirical data by (Daamen et al. 2010) shows that different merge locations are used during free flow and during congestion. It is found that during free flow the merge locations are lognormally distributed. The peak is before half of the acceleration lane. In (Schuurman 1991) it was found that approximately 75% of the merging vehicles merge within the first 200 m of the acceleration lane (no congestion). During congestion the merge locations are more spread along the acceleration lane. This is caused by the fact that vehicles deliberately overtake vehicles on the motorway during congestion. Analysis of the simulation for the no platooning case indeed reveals a spread caused by congestion as can be seen in Figure D.9. The majority of the vehicles only merges after 200 m. This is compared with the no platooning case without congestion (Figure D.10). Indeed vehicles merge earlier and about 78% of the vehicles merge within 200 m, roughly corresponding to the value found by (Schuurman 1991).

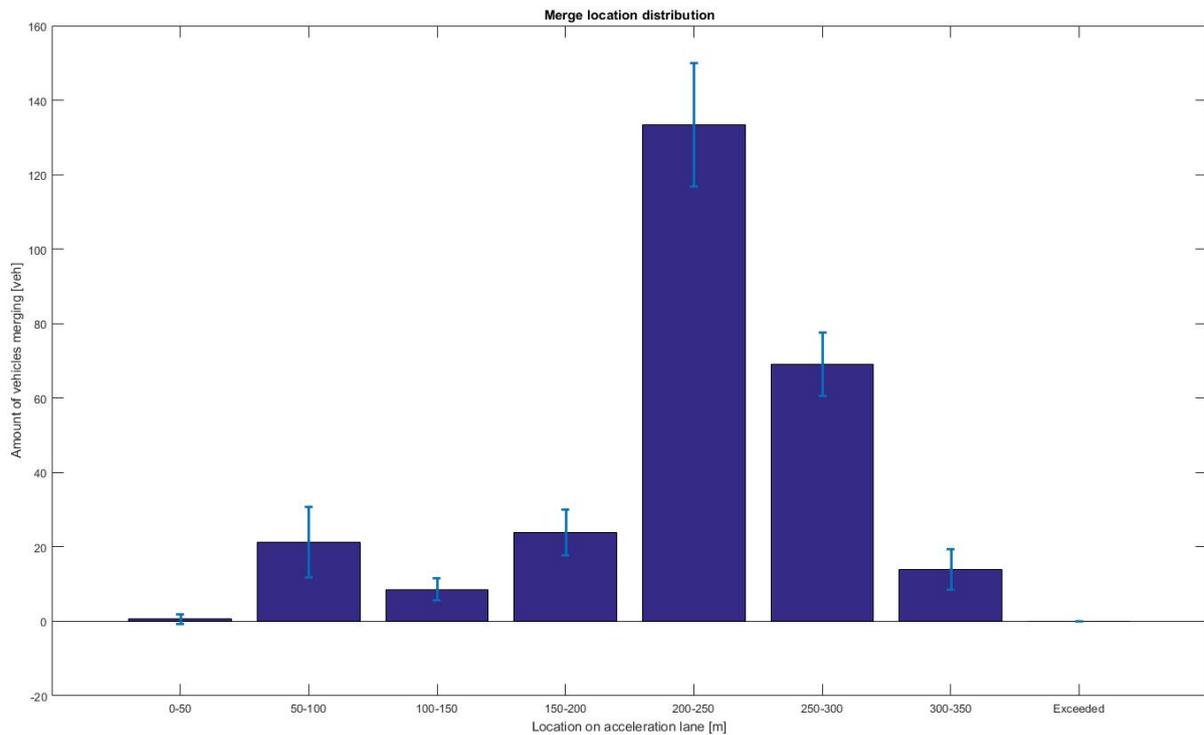


Figure D.9: Merge location distribution with error bars for the standard deviation (no truck platooning, congestion case).

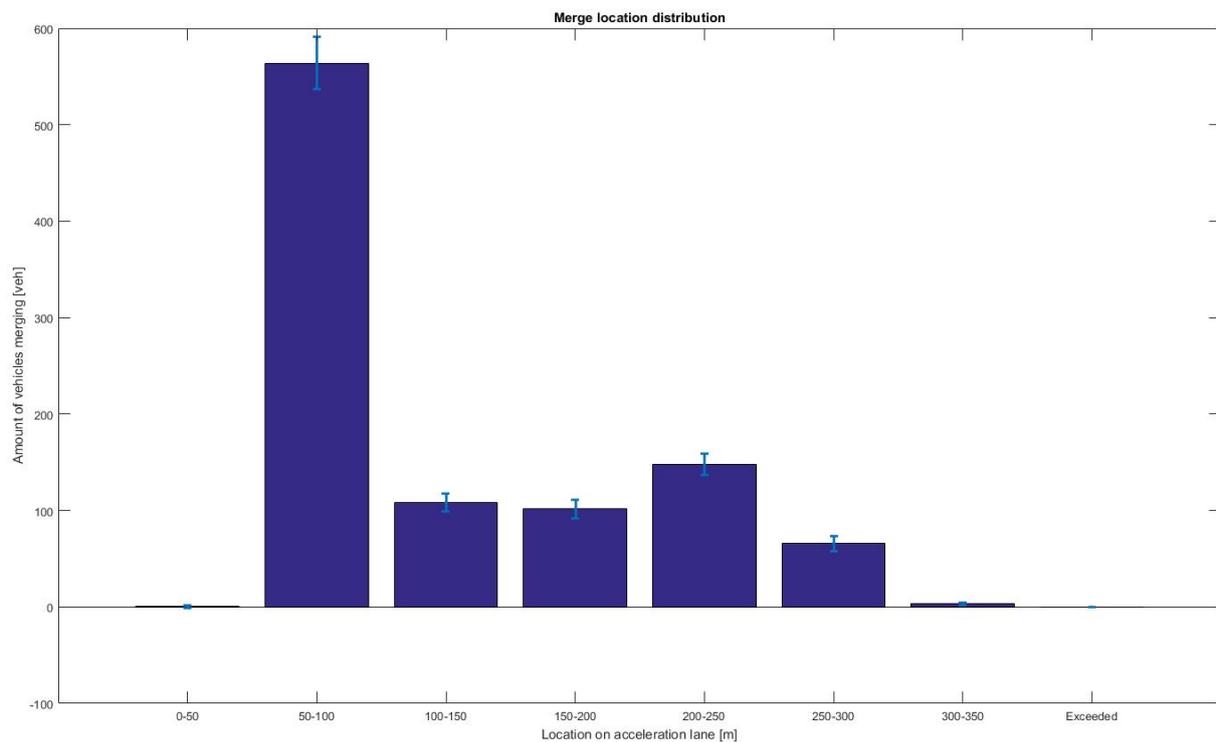


Figure D.10: Merge location distribution with error bars for the standard deviation (no truck platooning, no congestion case).

Merging speed

(Marczak et al. 2013) found that the merge location has no relation with the merging speed. They also found that there is a large variation in merging speed among drivers. When the merge location is plotted against time for the simulation test runs of all cases, it is indeed observed that this

relation is non-existent. This thus also validates the merging behaviour displayed by the simulation model. An example scatter plot of the relation between the merge location and the merging speed obtained from one of the simulation test runs is given in Figure D.11.

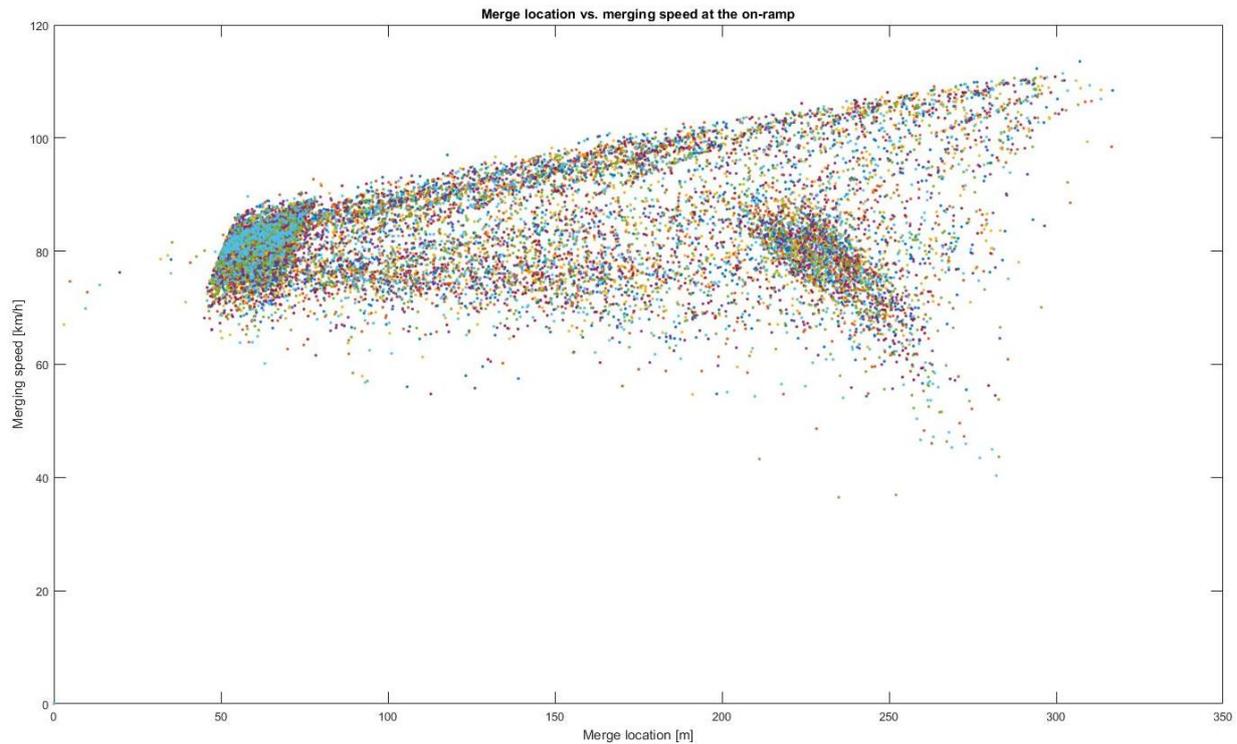


Figure D.11: Merge location vs. merging speed scatter plot (no platooning, no congestion case).

Gap acceptance

The distribution of time gaps of all vehicles in the network gives an indication of the minimum accepted gap as well as the average gap and its standard deviation. Figure D.12 and Figure D.13 show the time gap distributions of the simulation test runs for the congestion and no congestion cases respectively. The smallest gaps observed are 0.8-0.9 s (congestion case) and 0.4-0.5 s (no congestion case). A logistic distribution (the red line) was fitted to the gap distribution since it gives the best fit, although it fails to give a good fit especially for the high peak at 1.2-1.3 s (corresponding to the desired time gap of passenger cars) and the peak at 1.5-1.6 s (corresponding to the desired time gap of trucks). However, it does give insight into the average gap and its standard deviation. It reveals that the average time gap maintained in the no congestion case is slightly smaller.

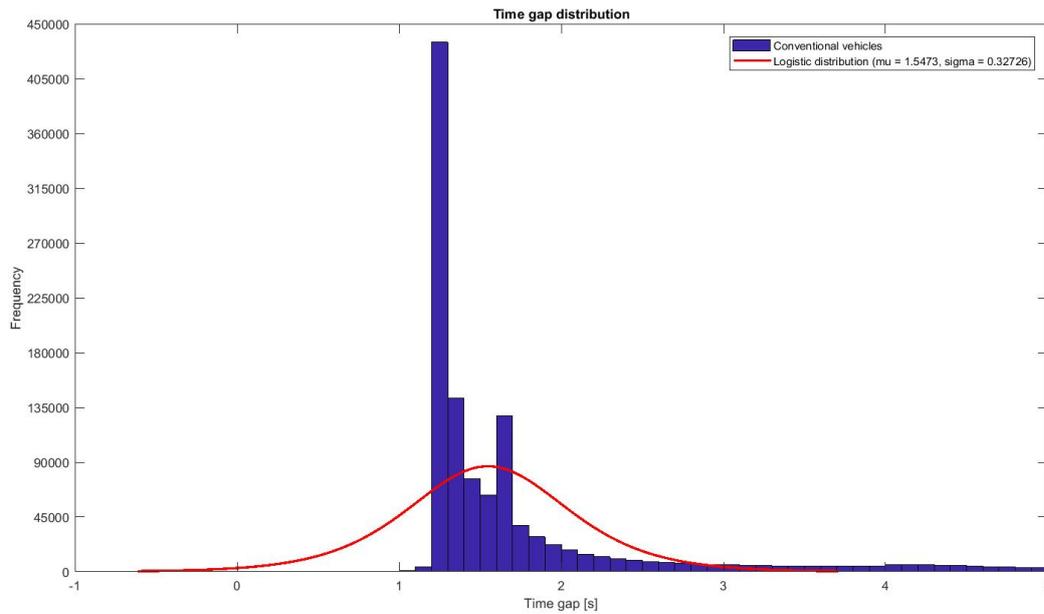


Figure D.12: Time gap distribution of the simulation test run (no platooning, congestion case).

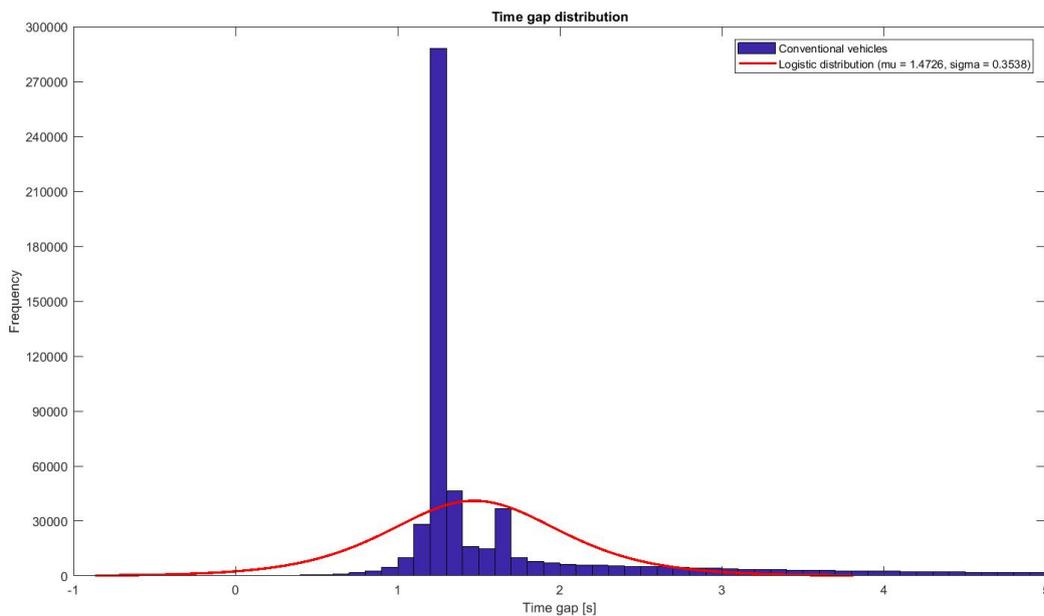


Figure D.13: Time gap distribution of the simulation test run (no platooning, no congestion case).

The smallest accepted gap that was observed in the empirical data set in (Daamen et al. 2010) is between 0.75 and 1.0 s. Cases in which the gaps between the merging vehicle and the new leader and follower vehicles is less than 0.25 s were also observed. These small gaps grow over time, indicating relaxation behaviour. Slightly smaller gaps are accepted at the end of the acceleration lane than at the beginning. In (Schuurman 1991) a similar conclusion on acceptance of extremely small gaps was found, namely that approximately 50% of merging vehicles will accept gaps smaller than 0.5-1.2 s. In the simulation test runs the smallest gap is never smaller than 0.4-0.5 s, showing that the minimum accepted gap in simulation is reasonable, although even smaller gaps have been observed in reality. This might result in a slight overestimation of merging problems in simulation.

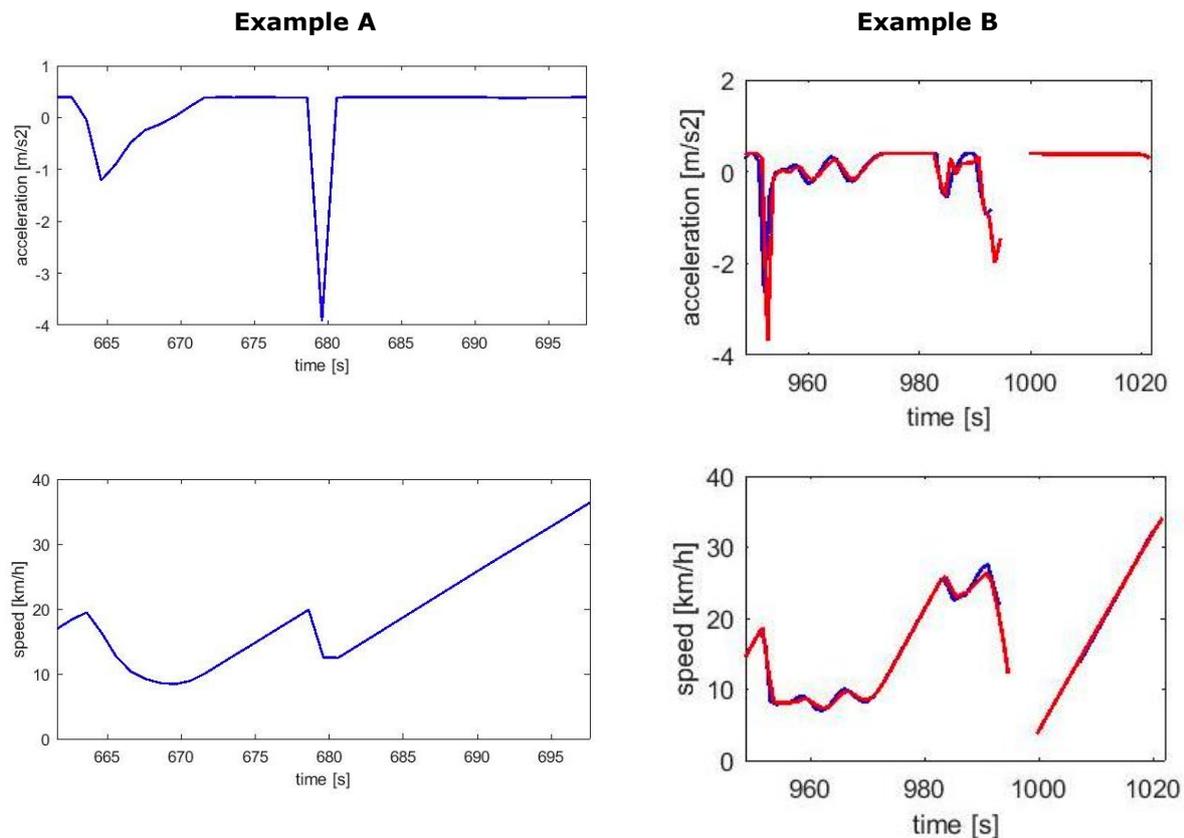
As described in section 2.3, gaps maintained and accepted by vehicles are relatively small if there are a lot of non-automated platooning trucks in the same lane. This justifies the modified minimum gap accepted by other drivers when changing lanes towards a truck platoon.

Truck platooning also has an effect on the gaps maintained by other drivers (see section 2.3) (Gouy et al. 2014). It was found that vehicles passing a platoon maintain significantly smaller gaps when the platoon maintains gaps of 0.3 s. This is an effect that is not accounted for in the simulations. This might limit the validity of the simulation set-up. Yet it has been chosen to ignore this effect since the size of the adapted gaps is unknown and the knowledge of this phenomenon still limited.

Truck platoon acceleration and speed profiles with corresponding gaps

Acceleration and speed profiles with corresponding gaps of all platooning trucks passing the on-ramp are obtained from vehicle trajectory data. Two sets of graphs with the acceleration and speed profiles with corresponding gaps of some platooning trucks are given as examples in Figure D.14, similar to the graphs of the Matlab test scenarios. The left graphs represent the platooning truck for which the most firm braking and the smallest minimum distance gap was observed. This might be comparable to an emergency braking situation. Only one vehicle is visible since there is apparently no more follower. The graphs on the right represent two platooning trucks in a stop and go situation with lots of fluctuation in acceleration and speed.

Figure D.14a shows that the extreme braking results in a minimum distance gap of only 1 m, but the gap size is quickly restored. Figure D.14b shows firm braking of a platoon member because of which its predecessor needs to brake even more hard. Both vehicles manage to maintain a gap larger than the 3 m safety margin. The platoon then reaccelerates and needs to perform another braking manoeuvre. This time the most downstream platoon member has more difficulty to maintain a safe gap as it nearly goes to 1 m. However, both platoon members reaccelerate quickly and the gaps start increasing again.



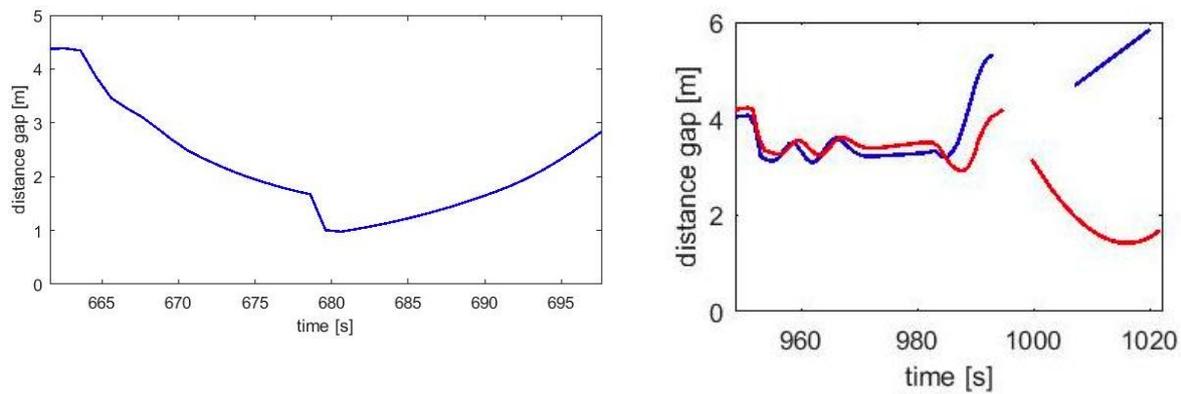


Figure D.14: Acceleration and speed profiles with corresponding gaps in two different example situations a and b. (N.B.: discontinuities in the graphs of example B occur due to the search conditions used to identify the platooning trucks.)

Apart from these two examples, the acceleration and speed profiles are checked for every single platoon in the simulation so that no unsafe situation goes unnoticed. In this way it is observed that a collision of platoon members never occurs, although the minimum gap observed is approximately 1 m. This is less than the standstill distance of 3 m. All these critical situations occur either during congestion or during the onset of congestion. Thereby most critical situations occur during congestion, so at low speeds. The impact of a collision at low speeds is obviously smaller than at higher speeds, so the majority of critical situations have a limited risk. However, there are also critical situations that occur at higher speeds and thus with higher risk. Moreover, the number of times a platooning vehicle needs to brake at almost full strength is very small.

Analysis of the profiles thus reveals plausible driving behaviour, although with a worse performance of the (C)ACC controller than one would expect from the outcome of the Matlab tests. The performance is however still sufficient as no collisions occur with the smallest possible CACC time gap and the number of critical situations at high speeds is limited.

Appendix E

Results (C)ACC controller performance verification in typical driving scenarios

This appendix gives all results of the verification of the performance of the proposed (C)ACC controllers in the typical driving scenarios. The parameter values and vehicle capability settings used are first described in section E.1. Subsequently, an elaborated description of the typical driving scenarios is given in section E.2. Finally, the simulation results are presented in graphs and briefly explained for the different controllers in section E.3.

E.1 Parameter values and vehicle capability settings

The proposed controller is tested in the most extreme situation. This means a CACC time gap of 0.3 s for the platoons is applied as well as a ACC time gap of 1 s. The standard parameter values of Table E.1 are used unless stated otherwise. For vehicle acceleration capabilities and IDM+, the default calibrated values of MOTUS are used, i.e. a max. acceleration of 2 and 0.4 m/s², a max. deceleration of -6 and -4 m/s², a comfortable acceleration of 1.25 and 0.4 m/s² and a comfortable deceleration of 2.09 m/s² for passenger cars and trucks respectively. The system delay is set equal to the time step of 0.2 s, while actuator lag is set to zero.

Table E.1: Standard (C)ACC controller parameter values used in the typical driving scenarios.

Parameter name	Symbol	Value
Standstill distance (passenger car/truck) [m]	s_0	2 / 3
Desired time gap (manual driving/ACC) [s]	t_{des}	1.2 / 1
Control parameter cruise control	k_v	0.3
Control parameter gap error (without/with collision avoidance system)	k_s	0.1 / 0.18
Control parameter relative speed error (without/with collision avoidance system)	$k_{\Delta v}$	0.58 / 1.93
Aggressiveness coefficient collision avoidance function	Q	1
Perception range coefficient collision avoidance function	P	100
Transition of control threshold	$\Delta v / S$	10/150

E.2 Typical driving scenarios

The typical driving scenarios considered are the following:

- *Normal scenario*: a scenario with normal driving conditions. A platoon predecessor drives at 80 km/h, after some time accelerates to 90 km/h, then after some time decelerates to 50 km/h, with acceleration rates of 0.4 (max. acceleration rate of the trucks) and -0.5 m/s respectively.
- *Stop and go scenario*: a scenario representing congestion, in which the platoon leader might have to brake to a complete stop and then reaccelerate to follow its predecessor. The platoon predecessor initially drives at 20 km/h, after some time brakes to a complete stop, then after some time reaccelerates to 50 km/h and finally after some time brakes again to a complete stop. The braking rate is set at 0.5 and 1 m/s².

- *Emergency braking scenario*: a scenario in which the platoon predecessor brakes hard at 4 (max. braking rate of a truck) to 6 (max. braking rate passenger car) m/s^2 starting from 90 km/h to a complete stop, with a high risk of collision.
- *Cut in scenario*: a scenario in which a passenger vehicle suddenly cuts in in front of the first platoon follower, resulting in a sudden reduction of the gap.
- *Cut out scenario*: a scenario in which the first platoon follower decides to leave the platoon by disabling the CACC controller and switching to the ACC controller, with an increased desired time gap of 3 s. This simulates a scenario in which the truck driver anticipates on a merging problem by creating room for a merging vehicle. The follower leaves with a deceleration of $0.5 m/s^2$. After some time, a passenger vehicle merges in front of the leaving truck, after which the leaving truck catches up with its new predecessor.
- *Approaching/catching up scenario*: a scenario in which the platoon approaches a slower predecessor with 85 km/h and a relative speed difference of 10 to 80 km/h, with steps of 10 km/h. This simulates the collision risk at high speed differences, in the extreme case approaching a (almost) standstill vehicle.
- *Longer platoon scenario*: a scenario with similar driving conditions as in the normal scenario, but now the number of vehicles in the truck platoon is increased to eight. This scenario checks the stability properties of the platoon.

E.3 Simulation results

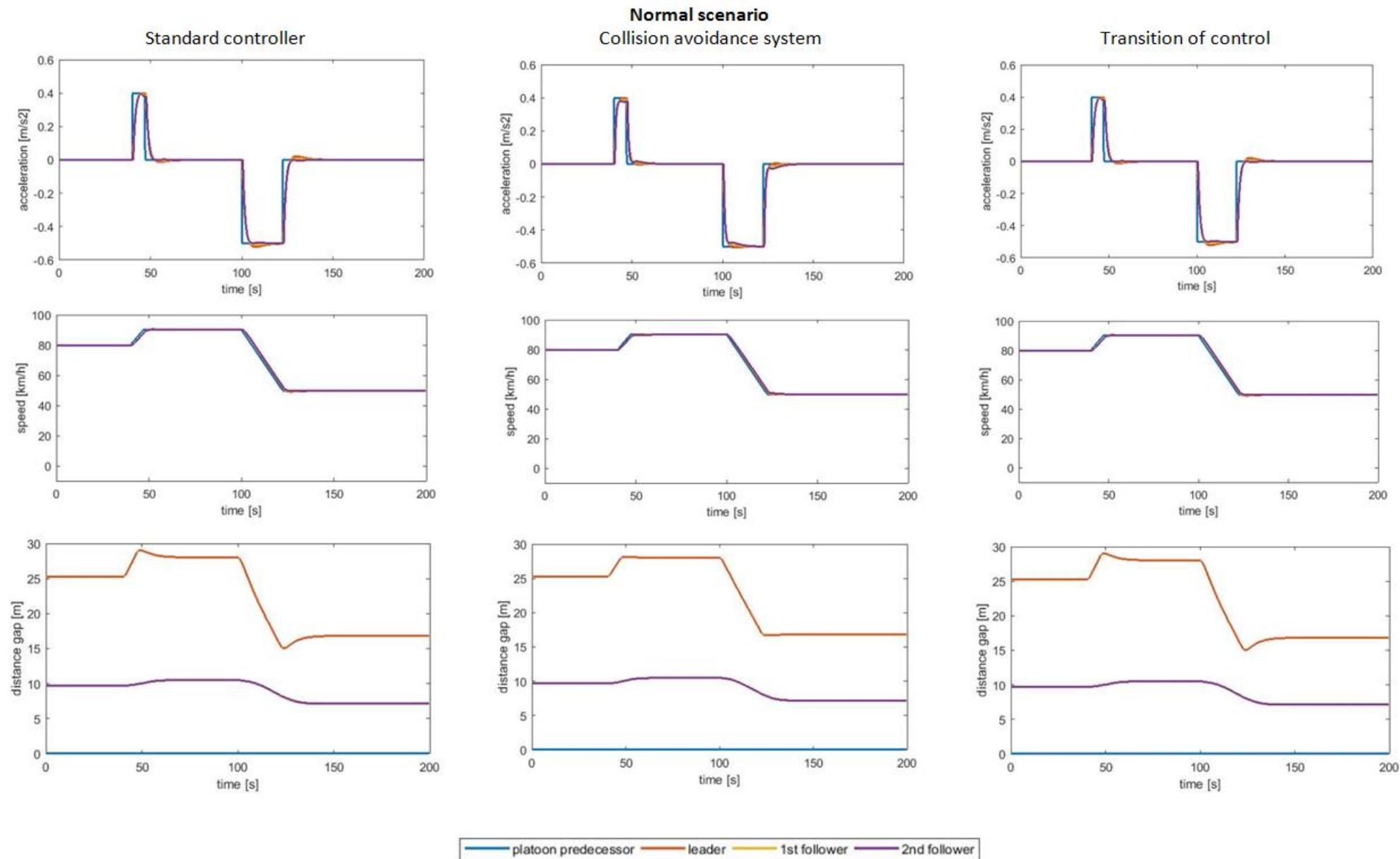


Figure E.1: Normal scenario - all three controllers manage to generate plausible and safe driving behaviour.

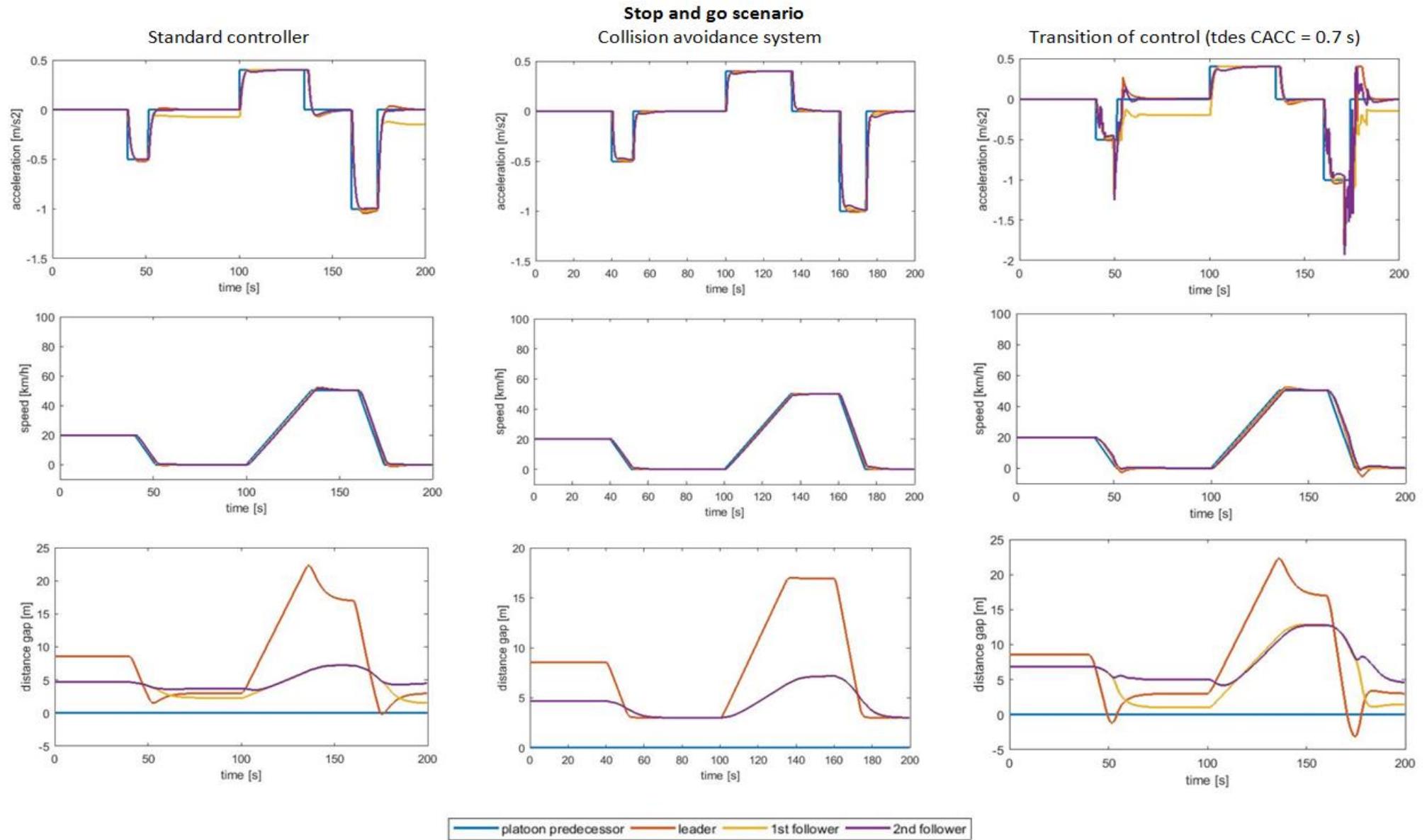


Figure E.2: Stop- and go scenario - only the controller with collision avoidance system is able to prevent a collision. The controller with transition of control even still fails for a larger CACC gap of 0.7 s.

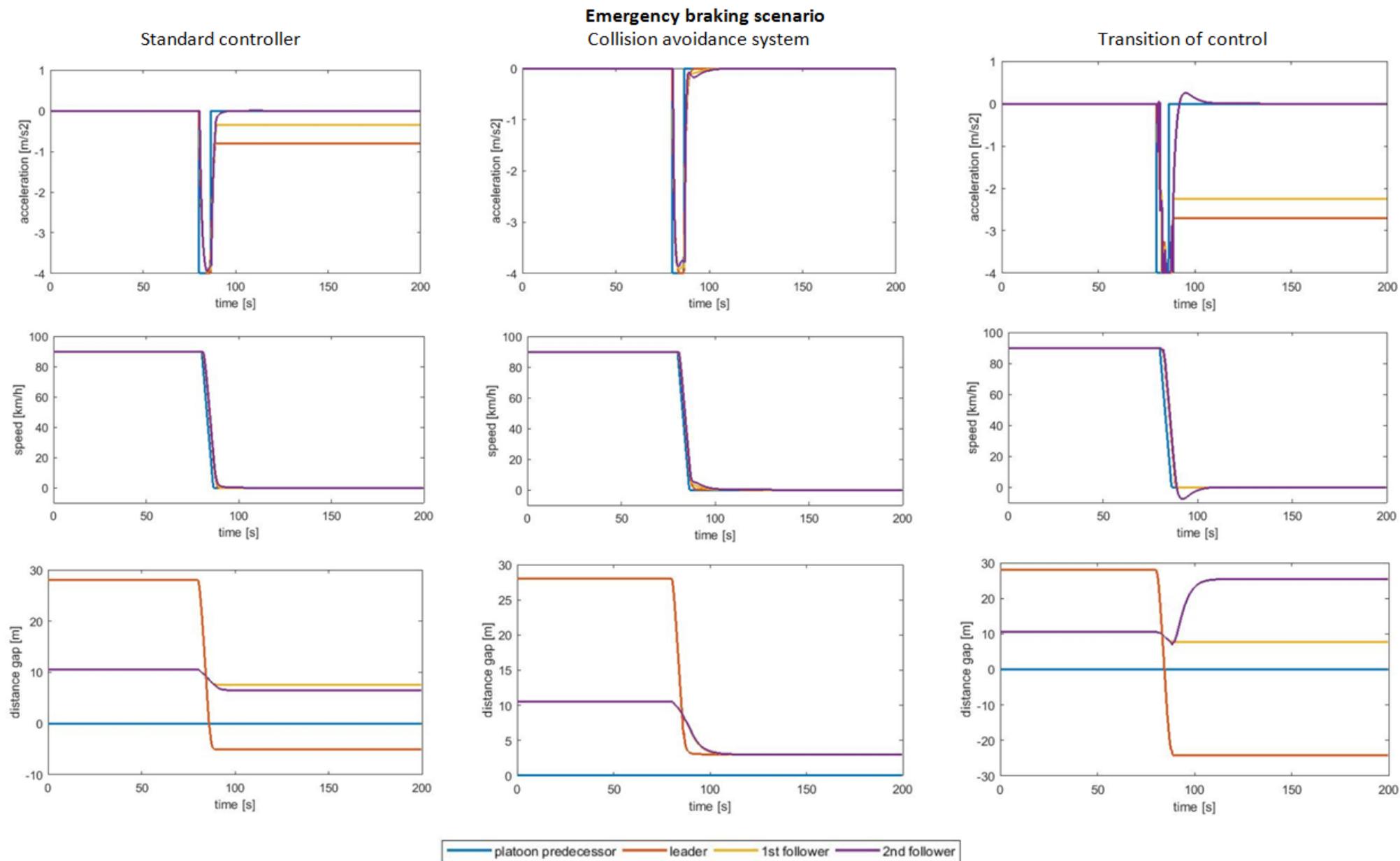


Figure E.3: Emergency braking scenario - only the controller with collision avoidance system is able to prevent a collision.

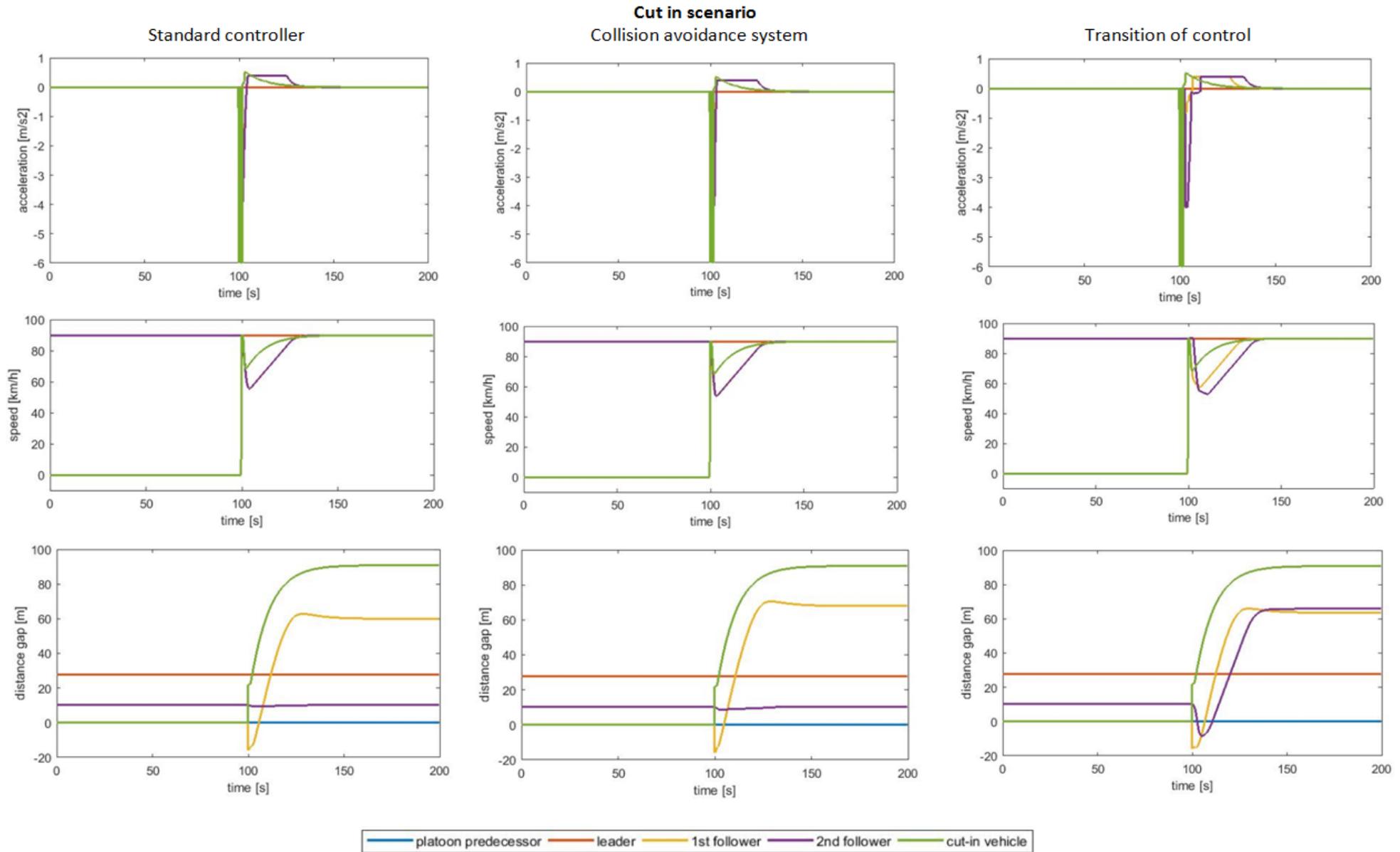


Figure E.4: Cut in scenario - none of the controllers is able to prevent a collision of the first follower with the cut-in vehicle. This is not necessarily a problem because the cut-in vehicle here accepted an extremely small gap of 0.3 s, which is not realistic.

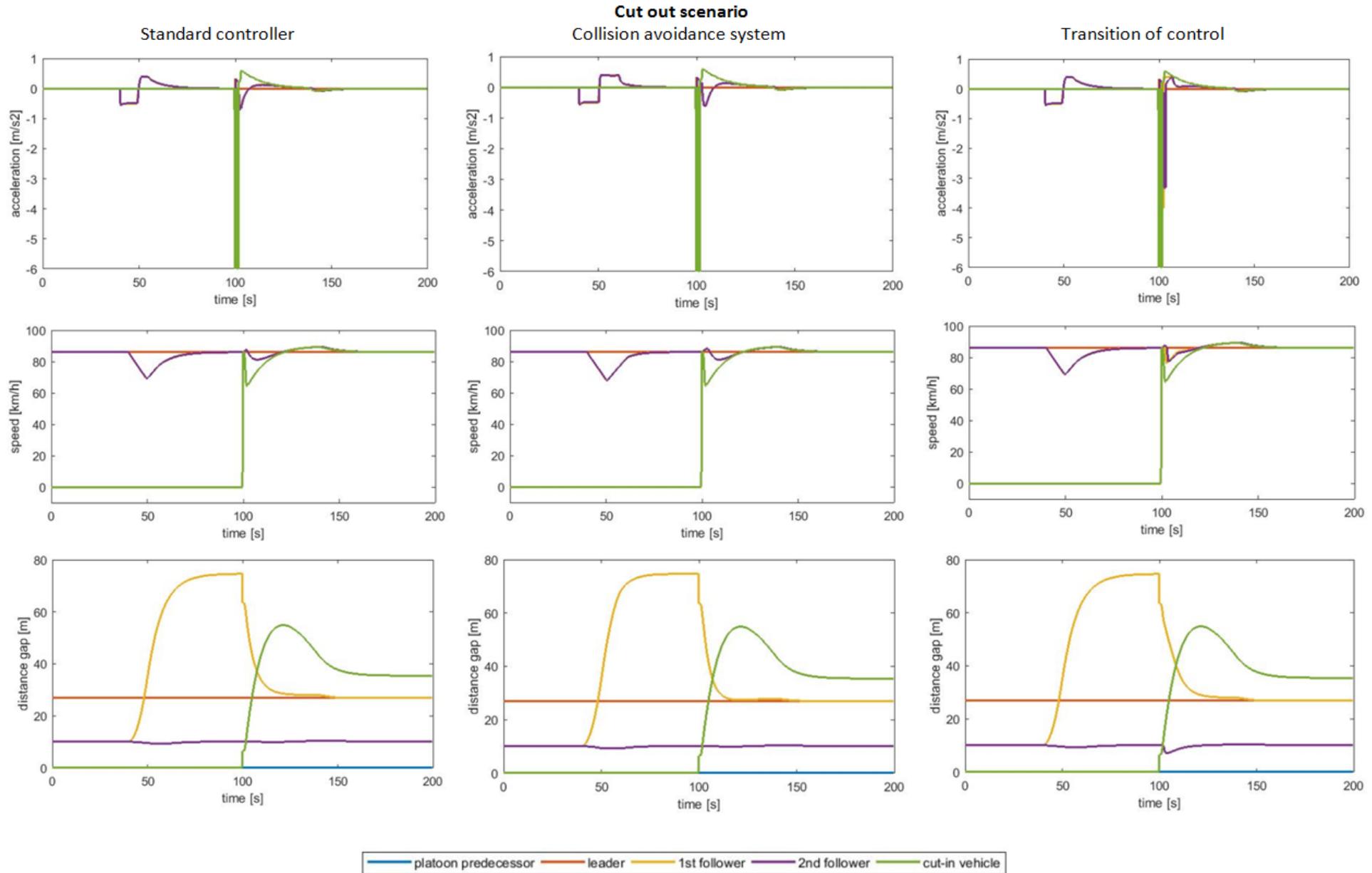


Figure E.5: Cut out scenario - the driving behaviour of controller with transition of control is much less smooth than that of the other controllers.

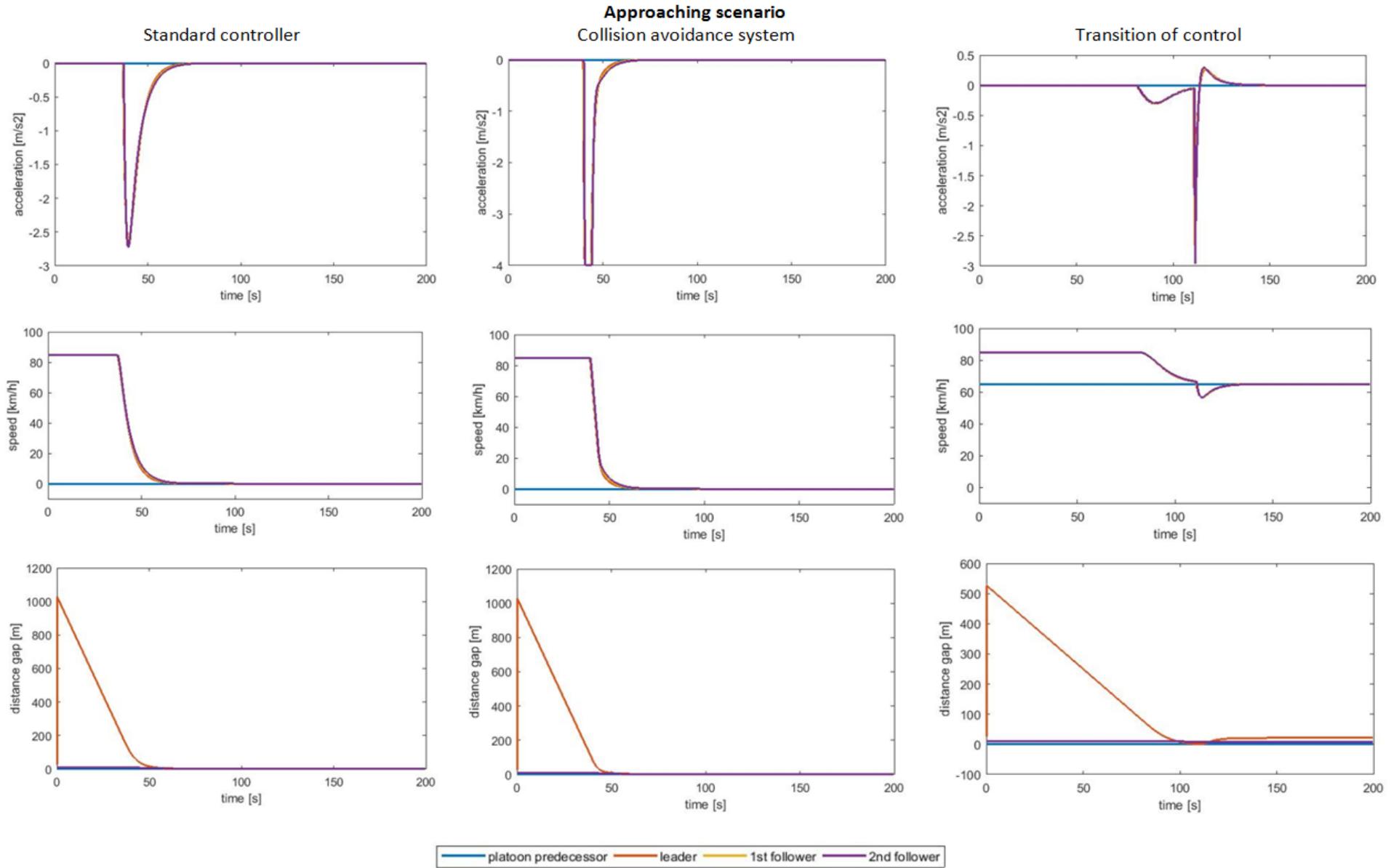


Figure E.6: Approaching scenario - the standard controller and the controller with collision avoidance system are able to prevent a collision when approaching a standstill vehicle at full speed, while the controller with transition of control is hardly able to prevent a collision with a speed difference of only 20 km/h.

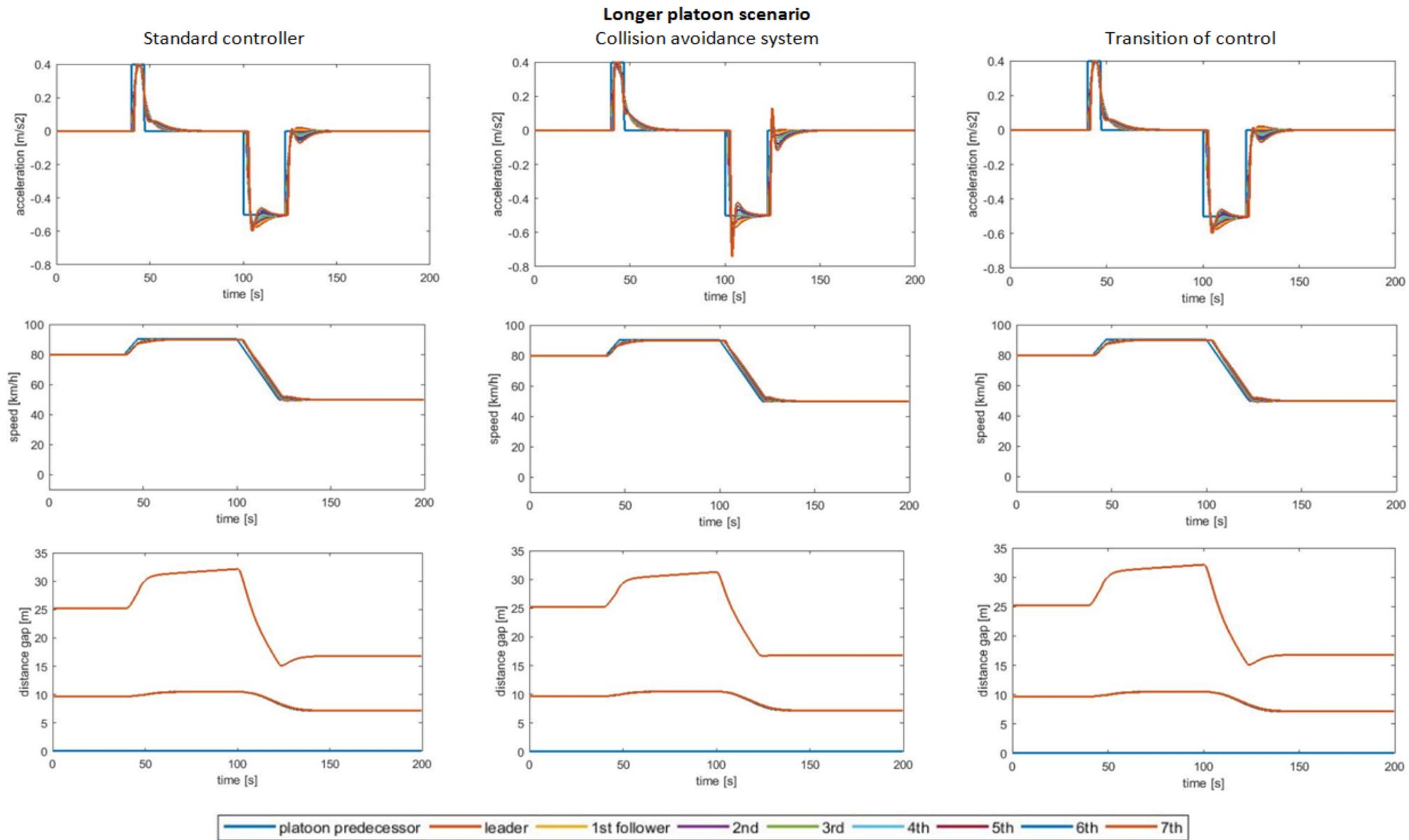


Figure E.7: Longer platoon scenario - string stability of the platoon can be observed since the oscillations of the acceleration response are attenuated in upstream direction, for all controllers.

Longer platoon scenario: single versus multiple predecessor anticipation

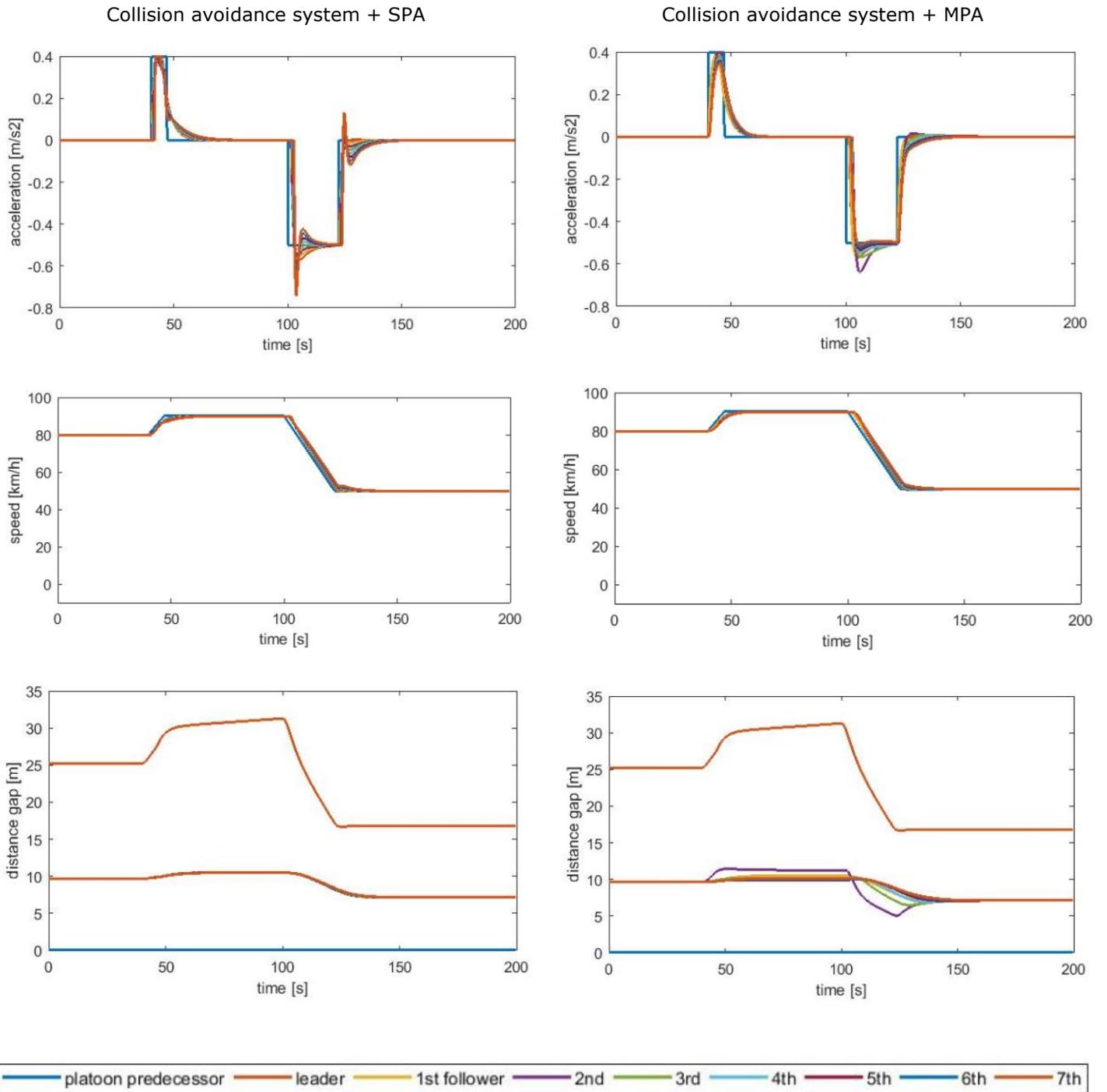


Figure E.8: Longer platoon scenario - SPA vs. MPA - The controller using MPA clearly shows the potential of MPA to smoothen and attenuate the acceleration responses, however this also leads to more fluctuation of the distance gaps.

Appendix F

Analysis of INWEVA intensities A67 Eindhoven-Venlo 2016

This appendix gives a detailed explanation of how the traffic intensity data INWEVA was analysed to retrieve the desired traffic intensities for both the motorway and the on-ramp. Special attention is paid to the distribution of vehicles over the lanes as well as the arrival time distribution at the on-ramp. These are both crucial factors for interaction of traffic on the motorway with traffic on the on-ramp.

F.1 Motorway

According to the INWEVA data the share of heavy freight traffic on the A67 between Eindhoven and Venlo varied between 13 and 45%, corresponding to a maximum of approximately 600 trucks/h on the A67 in 2016, depending on the time of day, the location and driving direction. It appears that for all on-ramps and driving directions, the share and amount of heavy freight traffic is typically highest just before the morning peak and after the morning peak until just before the evening peak. This means that truck drivers might be avoiding periods of the day with heavy traffic.

In contrast to the traffic intensity pattern during the day of heavy freight traffic, the pattern for the traffic as a whole does show the highest intensities during the peak periods. Thereby the evening peak intensity is typically significantly higher than the morning peak intensity. Since the share of heavy freight traffic is also typically somewhat higher during the evening peak than during the morning peak, this means that the evening peak is the normative peak period for the high traffic intensity on the motorway.

Since the share and amount of heavy freight traffic are highest just before the morning peak as well as between the morning and evening peak, the effect of truck platooning during these periods could be higher than during the normative peak period, even though the traffic intensity for the traffic as a whole is lower. Therefore, the middle of the day is chosen as the normative period with medium traffic.

A period late in the evening is chosen as the period with low traffic. At these hours, the traffic intensity is significantly lower than during the day, while still being significantly more than during the night. This is preferred over choosing a period during the night, since traffic intensities during the night are so low that it is expected that no visible effect of truck platooning will occur.

F.1.1 Lane distribution

The INWEVA data only gives the intensities for both lanes of the motorway together. It does not tell how the vehicles are distributed over the two lanes. To ensure that this distribution over the lanes in the simulations is realistic, some research has been performed.

The distribution of traffic over the lanes depends on the traffic flow and density on the motorway (Wu 2005, Knoop et al. 2010). At very low flows, nearly all traffic will be in the right lane and the left lane remains unused. As flow increases, the left lane will be used more. Especially when there are lots of slower vehicles (such as trucks) in the right lane, drivers will prefer the left lane to be able to maintain their desired speed. Similarly, in the neighbourhood of an on-ramp, drivers also sometimes prefer the left lane over the right lane to allow on-ramp vehicles to merge (Knoop et al. 2010).

The distribution of traffic over the lanes has been researched (Wu 2005, Knoop et al. 2010) and quantified for motorways with different numbers of lanes. From this research the distribution was estimated for all four traffic intensities applied as shown in Table 4.1.

F.2 On-ramp

The intensities on the on-ramp typically show the same pattern as the pattern of the motorway traffic intensities. The highest intensities thus occur during the peak periods. Again, the evening peak is typically higher than the morning peak.

The pattern of the share of heavy freight traffic on the on-ramp highly varies per ramp considered. Some ramps show the largest share in between the morning and evening peak, while others show the largest share during the peak periods. Others even show the largest share during the evening or early morning.

Depending on the on-ramp and time of day, the share of heavy freight traffic on the on-ramp can vary heavily, for instance between 16 and 49%. Some on-ramps have only very limited freight traffic, whereby the share is never larger than 2%.

F.2.1 On-ramp speed limit

The speed limit of the on-ramp is 50 km/h. Vehicles on the on-ramp will only start accelerating approximately 100 m before the start of the acceleration lane. This matches the required acceleration length according to Dutch design standards (Rijkswaterstaat 2015).

F.3 Combination motorway and on-ramp

Although the evening peak is the normative peak period for the high traffic intensity on the motorway, an analysis of the intensity data of the on-ramps reveals that the normative combination of intensities of the motorway and the on-ramp is in fact during the morning peak. This is because the intensity on the on-ramp for that period is exceptionally high when compared to the evening peak. Therefore this is taken as the normative intensity for the high intensity scenario.

F.4 Number of trucks versus intensities

Another consideration in choosing intensities is the number of trucks on the motorway in relation to the intensity on both the motorway and the on-ramp. This consideration popped up when analysing the data to choose a suitable medium traffic intensity. For this research it was preferred to choose a somewhat lower motorway intensity in combination with a large share of trucks and a large on-ramp intensity rather than a higher motorway intensity in combination with a large share of trucks, but a small on-ramp intensity. In that way the effect of truck platooning on merging will be the largest since the increase of the number of merging vehicles is significantly larger than the decrease of the number of trucks on the motorway.

Given the above considerations, the traffic intensities selected to use in the simulations are according to Table 4.1. The high and medium traffic intensity result in approximately 350 heavy trucks/h on the motorway, the low traffic intensity results in approximately 300 heavy trucks/h on the motorway. This difference is thus very small. The main difference between the scenarios therefore is reflected in the number of other vehicles on the motorway and the on-ramp. Notable is furthermore the large number of merging vehicles in the medium scenario and the large share of trucks on the on-ramp in the low scenario.

F.5 Distribution of arrival times

The distribution of arrival times used by MOTUS' vehicle generator is chosen to represent an exponential distribution. This is a common distribution used in traffic modelling (Mathew 2014, Mathew 2014). It ensures vehicles are generated with exponentially distributed inter-arrival times, so vehicles might be far apart but also very close together and arrivals are independent of each other. An important assumption of this distribution is that the traffic arrival pattern is random (Chandrasekaran 2017, Wilson 2017). In the case of motorway traffic this assumption is defensible since the arrival times depend on many factors such as traffic density, the vehicles classes present, driver's desired speeds and the characteristics of the underlying road network. In reality traffic indeed often does not arrive uniformly distributed but rather in groups with large variations in gaps (Mathew 2014). The exponential distribution is able to mimic this arrival pattern.

Truck platoons are thus not generated by the vehicle generator of MOTUS, but are formed in the first kilometres of the network. To make sure that the platoons have formed before reaching the on-ramp, the length of the network upstream of the on-ramp therefore has to be long enough to achieve that. It was found that a length of 4 km before the on-ramp is sufficient to ensure timely platoon formation, hence this is the length of the network before the on-ramp.

Appendix G

Performance indicators

This appendix provides a detailed description of the performance indicators used, including the mathematical definitions.

G.1 Traffic performance indicators

To quantify the traffic performance of scenarios, the following traffic performance indicators are used. Macro level indicators are used to capture network effects and micro level indicators are used to capture effects on a specific area or (group of) vehicle(s).

G.1.1 Macro level indicators

The macro level indicators can be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical indicators

- **Speed- and flow-contour plots.** These give insight into the spatio-temporal developments of aggregate traffic speed and thereby in jam patterns and traffic flow dynamics.
- **Fundamental diagrams.** These give insight into the traffic states observed. They are given in the density-flow plane, the density-speed plane and the flow-speed plane. A distinction is made between the area upstream of the on-ramp, the on-ramp area and the area downstream of the on-ramp, so that differences in traffic states between these areas can be observed. A distinction is also made between the left and right lane to be able to observe differences in traffic states between the lanes.

Global value indicators

- **Total time spent (TTS)** in the network. The TTS is calculated from the vehicles' trajectories in the simulation by taking the sum of the time spent in the network by each individual vehicle over all vehicles generated during simulation (**equation (G.1)**). It gives an indication of network performance expressed in time. It is advantageous over a delay indicator since it does not require defining a base case without delay, which is subject to uncertainty.

$$TTS = \sum_{i=1}^{N_{veh}} tS_i \quad (\text{G.1})$$

Where:

TTS : total time spent in the network by all vehicles [h]

tS_i : time spent in the network by vehicle i [h]

N_{veh} : total number of vehicles generated in the network during the simulation period

- **Maximum outflow (QoutMax).** It is calculated by repeatedly calculating the average outflow during an aggregation period of five minutes using a moving average method that moves one minute per calculation and then taking the maximum calculated value (**equation (G.2)**). The aggregation period of five minutes prevents a bias in the result. Flow data from the most downstream detector is used. This method is similar to the FOSim method (Henkens and Tamminga 2015). It gives an indication of road throughput so that possible capacity effects of truck platooning can be noticed.

$$\bar{Q}_{out,t} = \frac{1}{p} \sum_{n=0}^{p-1} q_{out,t-n} ; Q_{out,max} = \max(\bar{Q}_{out,t}) \quad (G.2)$$

Where:

$\bar{Q}_{out,t}$: average output over period t till $t-p-1$ [veh/h]

p : aggregation period [min]

$q_{out,t}$: outflow during minute t [veh/h]

$Q_{out,max}$: maximum outflow during the simulation period [veh/h]

- **Mean absolute speed difference across the lanes (dVLane) (equation (G.3)).** The time mean speed is converted to space mean speed according to **equation (G.4)** to correct for overestimation of means. dVLane gives an indication of the degree of inhomogeneity of traffic states across the lanes. It can be further split in a value for the area upstream of the on-ramp, the area at the on-ramp and the area downstream of the on-ramp.

$$dVLane = \frac{1}{N_{det}} \sum_{x=1}^{N_{det}} (v_{smleft,x} - v_{smright,x}) \quad (G.3)$$

with

$$v_{sm} = \frac{1}{\frac{1}{N_{veh}} \sum_{i=1}^{N_{veh}} \frac{1}{v_i}} \quad (G.4)$$

Where:

$dVLane$: mean absolute speed difference across the lanes [km/h]

$v_{smleft,x}, v_{smright,x}$: space mean speed of detector x for the left and right lane respectively [km/h]

N_{det} : number of detectors considered

v_{sm} : space mean speed [km/h]

v_i : speed of vehicle i at the detector in question [km/h]

N_{veh} : number of vehicles passing the roadway segment

G.1.2 Micro level indicators

The micro level indicators can also be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical and global value indicators

- **Merging speed distribution.** This is a bar chart indicating the average merging speed observed for a specific part of the acceleration lane. It gives an indication of how well vehicles are able to synchronize their speed to the vehicles on the motorway and thereby the severity of disturbances in the traffic flow caused by the on-ramp. The **average merging speed and its standard deviation** are also deduced from the distribution to enable quick comparison to other simulation scenarios. It gives an indication of the degree to which the merging speed changes. Thereby it reveals possible increases in the severity of disturbances caused by increased speed differences with vehicles on the motorway. By also providing the standard deviation the spread of the merging speed is given as well,

indicating the probability that the merging speed is lower than desirable given the vehicle speeds on the motorway.

- **Gap distributions of the on-ramp area.** These give insight into the interaction between the merging vehicles and vehicles on the motorway, among which are the truck platoons. Distinction is made between equipped trucks and other traffic. It gives an indication of the frequency of occurrence of small inter-vehicle gaps that might result in disturbances in the traffic flow.

G.2 Traffic safety indicators

In order to determine how safe a certain simulation scenario is, it is necessary to define safety. In this thesis safety is defined as the expected number of crashes that occur in a certain period of time, differentiated by type of crash. A crash thereby is a collision between two or more vehicles.

G.2.1 Suitability of traffic simulation to evaluate traffic safety effects

Although it may be possible to obtain the number of collisions occurring in a simulation, it is difficult to predict these accurately (Gettman and Head 2003). Also, there may still be situations in which there is an increased risk of a collision occurring without a collision actually happening. The frequency of occurrence and the severity of such situations can give additional information on traffic safety, especially since the number of actual collisions in simulation is usually very small.

Traffic simulation is however not primarily meant to assess safety. Safety indicators are therefore not part of the 'standard' output that a simulation tool can deliver. Therefore it is necessary to define *surrogate* safety measures that give an indication of safety or at least the probability of increased crash rates.

G.2.2 Surrogate safety indicators

One common way to evaluate safety with surrogate safety indicators is to define conflicts. A conflict is defined as a situation in which two or more vehicles approach each other in time and space in a way that will lead to a collision if their movements remain unchanged. Both the frequency of occurrence and the severity of conflicts can indicate a safety issue. Strong braking and evasive manoeuvres might for instance indicate safety issues. There is general consensus that higher rates of traffic conflicts can indicate lower levels of safety (Gettman and Head 2003). However, indicators that define the frequency and occurrence of conflicts can only give a rough indication of the level of safety, since the total level of safety is influenced by many factors that are not all captured by these indicators. This means that these indicators indicate the extent to which a safety risk changes rather than the level of safety. However, these indicators can only compare a part of the level of safety of different situations and do not provide an absolute measure of safety.

Again macro level indicators are used to capture network effects and micro level indicators are used to capture effects on a specific area or (group of) vehicle(s). The macro level indicators that will be used to evaluate safety in the simulations are common indicators according to (Gettman and Head 2003, de Azevedo 2014, Behbahani and Nadimi 2015, Mahmud et al. 2017). They indicate the severity of conflicts and in case of a distribution also the frequency of occurrence. The micro level indicators that will be used focus on the safety of the merging vehicles at the on-ramp.

The relation between the proposed surrogates and crashes has not been proven, but is rather based on rules-of-thumb and common sense. This should be kept in mind when valuing the importance of the surrogate safety indicators.

Macro level indicators

The macro level indicators can again be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical indicators

- **Time to collision (TTC) distributions.** The time to collision is the time after which two vehicles will collide if they remain at their present speed and on the same lane (**equation**

(G.5)). These give insight into the severity and frequency of occurrence of dangerous situations that may lead to collisions. They are given for the on-ramp area to capture the interaction between the merging vehicles and the truck platoons, but also for the entire network to capture effects of truck platooning in upstream and downstream direction.

$$TTC_{i,t} = \frac{s_{i,t}}{v_{i,t} - v_{i-1,t}}; v_{i,t} > v_{i-1,t} \quad (\text{G.5})$$

Where:

$TTC_{i,t}$: time to collision [s]

$s_{i,t}$: distance gap of vehicle i with its predecessor [m]

$v_{i,t}$, $v_{i-1,t}$: speed of vehicle i and its predecessor $i-1$ respectively [m/s]

Global value indicators

- **Time-exposed TTC (TETTC)** and **time-integrated TTC (TITTC)**. The TTC distributions are further analysed by calculating the time-exposed TTC as well as the time-integrated TTC (**equation (G.6) and (G.7)**). The former is the duration of time that the TTC is less than a threshold value and the latter is the total TTC summation during that time. A suitable threshold value is chosen based on the minimum value that is still considered safe. The truck platoons are excluded from the analysis to enable a fair comparison between scenarios.

$$TETTC = \sum_{i=1}^{N_{veh}} \sum_{t=0}^T \delta_{i,t} * \tau_s; \delta_{i,t} = \begin{cases} 1 & \text{if } 0 \leq TTC_{i,t} \leq TTC_{min} \\ 0 & \text{otherwise} \end{cases} \quad (\text{G.6})$$

$$TITTC = \sum_{i=1}^{N_{veh}} \sum_{t=0}^T (TTC_{min} - TTC_{i,t}) * \tau_s; TTC_{i,t} \leq TTC_{min} \quad (\text{G.7})$$

Where:

$TETTC$: time-exposed time to collision [s]

$\delta_{i,t}$: discrete parameter of vehicle i at time t

τ_s : simulation time step [s]

N_{veh} : total number of vehicles generated in the network during the simulation period

T : simulation period [s]

$TTC_{i,t}$: time to collision of vehicle i at time t

TTC_{min} : time to collision threshold value [s]

$TITTC$: time-integrated time to collision [s²]

TTC threshold value

The TTC threshold value should be chosen such that it distinguishes between safe and unsafe vehicle encounters based on the TTC values. In past research, different thresholds have been adopted varying from less than one to approximately 8 s (Charly and Mathew 2016, Mahmud et al. 2017). The threshold depends on the traffic conditions and driver behaviour parameter settings (Charly and Mathew 2016). For example, the presence of different vehicle classes has an effect on the threshold as well as the desired time gap of drivers. The threshold is typically lower for urban areas with intersections than for rural roads. Moreover, a threshold should obviously not be chosen below the human reaction time (Mahmud et al. 2017). The threshold adopted in this study is 3 s since it is recommended for two-lane rural roads by (Farah et al. 2009, American Association of State Highway Transportation 2011, Mahmud et al. 2017).

Micro level indicators

The micro level indicators can again be categorized as either graphical indicators revealing traffic patterns in graphs or as global values that give one performance value for the entire network:

Graphical and global value indicators

- **Merge location distribution.** This is a histogram indicating the frequency of occurrence of merge locations and its standard deviation. It gives an indication of how well merging vehicles are able to merge. Late merging or even inability to merge might lead to dangerous situations. If a vehicle is (almost) unable to merge, it is shown in the bar chart by the bar representing the end of the acceleration lane. The **average merge location and its standard deviation** are also deduced from the distribution to enable quick comparison to other simulation scenarios. It gives an indication of the degree to which the merge location is shifted towards the end of the acceleration lane. By also providing the standard deviation the spread of the merge location is given as well, indicating the probability that the acceleration lane is exceeded.
- **Merging speed distribution.** Apart from serving as a traffic performance indicator, the merging speed distribution also serves as a traffic safety indicator. It gives an indication of how well vehicles are able to synchronize their speed to the vehicles on the motorway and thereby reveals potentially dangerous situations caused by speed differences. The **average merging speed and its standard deviation** are also deduced from the distribution to enable quick comparison to other simulation scenarios. It gives an indication of the degree to which the merging speed changes. Thereby it reveals potentially dangerous situation caused by increased speed differences with vehicles on the motorway. By also providing the standard deviation the spread of the merging speed is given as well, indicating the probability that the merging speed is lower than desirable given the vehicle speeds on the motorway.
- **Driving profiles of the platooning trucks.** The degree and frequency of accelerations and decelerations in these profiles give an indication of whether the truck platoons generate safe driving behaviour in all circumstances.

G.2.3 Conclusions on performance indicators

The performance indicators used to analyse the simulation output can be divided in indicators that quantify the traffic performance of scenarios and indicators that quantify the traffic safety of scenarios. For traffic performance indicators, indicators on macro level as well as micro level are used. They are either global values that capture performance of all vehicles in a single value or graphical indicators that visualize traffic patterns. As traffic safety indicators, surrogate indicators are used since safety is hard to measure in simulations. Again macro and micro level indicators as well as global value indicators and graphical indicators are used. Applying the indicators to the simulation output enables balanced comparison of simulation scenarios and gives a complete image of the performance.

Appendix H

Simulation output data management

This appendix gives a description of how the required amounts of simulation output data per simulation scenario are determined and how this data is managed to obtain reliable performance indicator values.

H.1 Sample size determination

The simulation scenarios are each run multiple times in MOTUS to account for different possibilities in the stochastic simulation variables, such as the desired speed of vehicles and the time of vehicle generation of vehicles of any vehicle class. The number of times that a simulation scenario is run depends on the required sample size that gives a reliable value of the performance indicators.

Before the simulations can be run, the sample size must be determined. This is the number of so called random seeds that is run for a simulation scenario.

MOTUS sets the stochastic variables such as the desired speed and vehicle generation randomly different for every seed. It generates a unique input per random seed. This returns identical results per seed for every run, which is very useful when analysing the effect of changing a certain variable. Therefore, the same random seeds should be used for every scenario to guarantee a statistically correct comparison.

Using multiple seeds can then create a statistically representative output if the number of runs with different random seeds is chosen large enough. The number of seeds necessary to get reliable output depends on the desired confidence interval, the standard deviation of the measured variable and the desired accuracy using the student t-distribution value according to **equation (H.1)**.

$$N \geq t_{\frac{1}{2}, a, N-1} \left(1 + \frac{1}{2} \xi^2\right) \frac{X_s^2}{X_d^2} \quad (\text{H.1})$$

Where:

$t_{\frac{1}{2}, a, N-1}$: the student t-distribution value

ξ : the abscissa or the normal distribution excess value

a : the desired reliability,

X_s : the sample standard deviation

X_d = the accepted deviation.

To determine the required sample size, the global value traffic performance indicators TTS, dVLane and Qoutmax are chosen as indicative. Ten test runs are performed with different random seeds, resulting in a mean and standard deviation of the indicators. The indicator with the largest standard deviation is then determining for the sample size. The desired reliability is set at 95%. The number of samples necessary for a reliable result of the average value is desired, so the n% excess value = 50% and thereby $\xi = 0$. The accepted deviation is chosen as 2% of the sample mean.

Iteratively determining the required sample size for several simulation scenarios (both with and without platooning) indicated that a sample size of 20 random seeds per scenario should suffice to obtain reliable data. Concluding, this means that the mean values of the aforementioned performance indicators are with 95% certainty no more than 2% different from the population mean.

H.2 Data management

The simulations are run and analysed using Matlab in three consequent steps:

1. Run each simulation scenario 20 times with different samples.
2. Combine the simulation data of all 20 samples per simulation scenario.
3. Compare the performances of the simulation scenarios in terms of the performance indicators.

Each simulation scenario run represents one hour of real-time traffic. In addition, a warm-up time of five minutes preceding this hour is taken into account. This is equal to the time it takes to fill the network. Simulation output is obtained from the virtual loop detectors in the road as well as from the vehicle trajectory data. The loop detectors register average vehicle speed and the number of vehicles that have passed during an aggregated time period of one minute. The vehicle trajectory data includes for each second the time stamp, vehicle speed, acceleration, longitudinal position on the lane, class ID, lane ID, lane change progress state (i.e. indicating, yielding or none), distance gap with the predecessor and relative speed difference with the predecessor. Only the data registered after the warm-up time is used for analysis. The (C)ACC controller used in all simulations is according to Table 3.1 with parameter values according to Table 3.2. The simulation model parameter values of the IDM+ and LMRS are according to **Appendix D**.

Once the simulations have been run the detector and trajectory data of all 20 samples are combined per scenario to obtain reliable values for the performance indicators. The means as well as the standard deviations of each indicator are calculated where relevant.

In the final step the performances of the simulation scenarios are compared in terms of the performance indicators.

Appendix I

Performance of the base scenarios

The base scenarios are the scenarios in which truck platooning does not take place. There are four different base scenarios: one for each traffic intensity. The on-ramp merging behaviour shown in the base scenarios is first presented in section I.1, after which the resulting traffic performance and safety on the motorway is elaborated on in section I.2. Conclusions on the performance of the base scenarios are given in section I.3.

I.1 On-ramp merging behaviour

The merging behaviour of the vehicles on the on-ramp is captured by analysing the merge location distributions and the merging speed distributions as defined in section 4.3.

I.1.1 Merge location distributions

The merge location distributions are similar for all three base scenarios without congestion. Most vehicles merge within 50 to 100 m after the start of the acceleration lane. Almost all vehicles have merged after 300 m. In the congestion scenario however, most vehicles merge at between 200 and 250 m after the start of the acceleration lane. Also, many vehicles still need to merge at between 300 and 350 m. In none of the scenarios vehicles are unable to merge in time. The merge location distributions correspond to the findings from empirical evidence as shown in **Appendix D**, confirming the validity of the merging behaviour shown. The merge location distributions are plotted in Figure I.1.

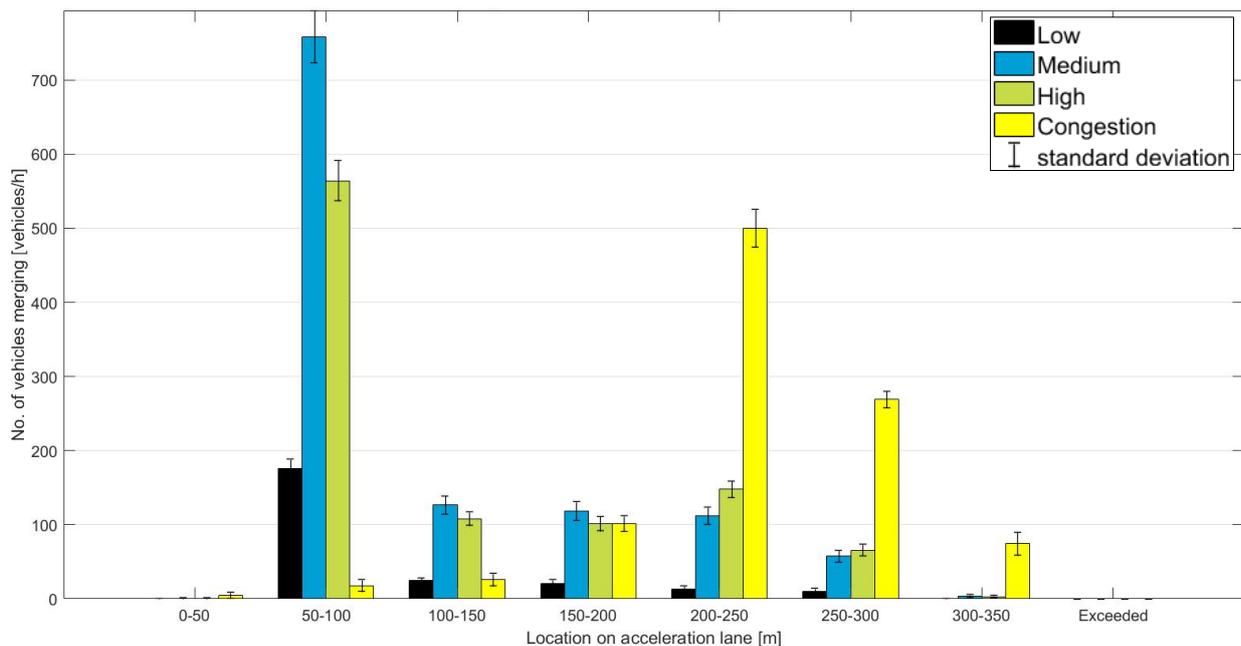


Figure I.1: Merge location distributions of the base scenarios for the different traffic intensities.

I.1.2 Merging speed distributions

For the base scenarios without congestion, the average merging speed increases slightly as one gets closer to the end of the acceleration lane. Thereby the difference between the scenarios and the standard deviation increases somewhat, whereby the average merging speeds are highest for the low traffic intensity and lowest for the high traffic intensity. For all three no-congestion base scenarios, the average merging speed is between 80 and 90 km/h. The congestion scenario shows a completely different pattern. Obviously merging speeds are much lower, with lowest average speeds of between 10 and 20 km/h observed in approximately the middle of the acceleration lane (100-250 m). At the beginning and the end, average merging speeds are a little higher (between 25-50 km/h). However, merging speeds show a large variability as reflected by the high standard

deviations. The average merging speed in the congestion scenario is approximately 17 km/h. The merging speed distributions are plotted in Figure I.2.

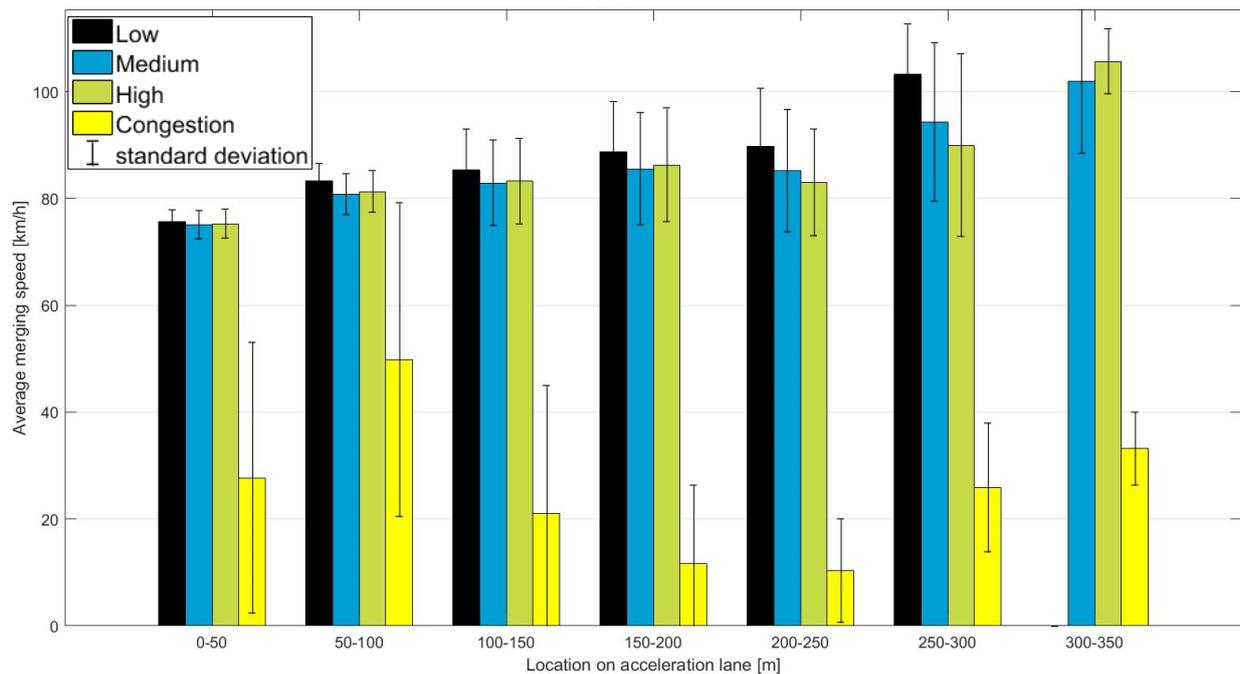


Figure I.2: Merging speed distributions of the base scenarios for the different traffic intensities.

The relatively low speeds in congestion between roughly 150 and 250 m after the start of the acceleration lane can be declared by the fact that this is where the queue is formed, as illustrated by a simulation screenshot in Figure I.3. This behaviour is declarable since vehicles are near the end of the acceleration lane and thus start synchronizing with the traffic on the motorway.

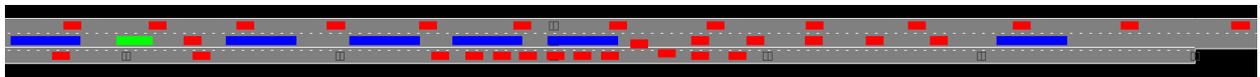


Figure I.3: Queue formation on the acceleration lane in the congestion base scenario.

I.2 Motorway traffic performance and safety

The effects that the on-ramp has on the performance of traffic and safety on the motorway is captured by analysing inter-vehicle gap distributions, the corresponding time-to-collision (TTC) distributions, as well as network level indicators total time spent, maximum outflow, average speed difference between the left and the right lane and the time-exposed and time-integrated time-to-collision. The resulting traffic states on the motorway are then captured in fundamental diagrams and flow- and speed-contour plots. An explanation of these performance indicators can be found in section 4.3.

I.2.1 Gap distributions

For the no-congestion base scenarios, the average time gap at the on-ramp area and its standard deviation decrease as traffic intensity increases. This is because vehicles will be closer together with increasing density. Average time gaps are higher upstream of the acceleration lane than downstream of the acceleration lane, which can be declared by increasing density downstream because of the inflow of vehicles at the on-ramp. In all cases, the smallest time gaps observed occur at the on-ramp area. This also counts for the congestion scenario. This might well be due to relaxation behaviour after merging. For the congestion scenario, the average time gap at the on-ramp area is higher than for the high traffic intensity scenario. This is caused by the congestion, in which speeds are so low that the safety/stopping distance starts playing a large role in the gaps maintained by drivers.

I.2.2 Time-to-collision distributions

For the no-congestion base scenarios, the TTC distributions are similar. The peaks in the observations lie around 12 s and hardly any observations below 10 s are observed, although the number of observations below 10 s slightly increases with increasing traffic intensity. The distribution looks much different for the congestion scenario. In this scenario the peak in the number of observations is at around 3.5 s and many observations as low as 1.4 s occur. This is caused by merging manoeuvres and shock wave effects in the traffic jam. Hence the time-exposed and time-integrated TTC are zero for the scenarios without congestion, but are significant for the congestion scenario as shown in Table I.1. In the scenarios without congestion, the smallest TTCs occur at the on-ramp area and hence are caused by merging vehicles. In the congestion scenario however, small TTCs also occur in the area upstream of the acceleration lane, induced by shockwave effects of the jam.

I.2.3 Total time spent (TTS)

For the low, medium and high traffic intensity base scenarios, the TTS is directly related to the traffic intensity. The relative difference in traffic intensity between the scenarios is approximately the same as the relative difference in TTS. This can be declared by the fact that there is no congestion in these three scenarios. This causes little difference in average vehicle speeds between the scenarios.

For the congestion base scenario, the relative increase in TTS is much higher, caused by reduced vehicle speeds during congestion. The TTS increase is approximately twice as large as could have been expected if there would not have been congestion. The TTS values are displayed in Table I.1.

I.2.4 Maximum outflow

Considering the maximum outflow, for the low traffic intensity an increase of approximately 25% above the total inflow (motorway + on-ramp) is observed and for the medium and high traffic intensities an increase of approximately 15% above the total inflow is observed. This difference might be caused by the fact that arrival patterns become more homogeneous as intensity increases (see **Appendix F**).

Considering the congestion base scenario, the maximum outflow gives an indication of the queue discharge rate (see **Appendix G**). This is because all detector measurements are obtained during congestion. This value is typically lower than the capacity. The queue discharge rate found is 3834 vehicles/h with a standard deviation of 224 vehicles/h. This is indeed lower than the estimated capacity, which is around 4100 vehicles/h for this composition of traffic (Henkens and Tamminga 2015). The maximum outflows found are given in Table I.1.

I.2.5 Average speed difference between the left and the right lane

The mean speed difference across the lanes becomes smaller with increasing traffic intensity. For the congestion base scenario, the speed difference is approximately half of that of the low intensity scenario. This convergence is in line with research findings (Mansvelter et al. 2014). The values found are displayed in Table I.1.

Table I.1: Performance of the base scenarios (means and standard deviations).

Scenario	Low	Medium	High	Congestion
TTS [h]	49(±2)	103(±3)	176(±3)	550(±14)
Max. outflow [veh/h]	1129(±60)	2695(±84)	3881(±134)	3834(±224)
dVLane [km/h]	31(±1)	29(±1)	25(±1)	14(±2)
TE-TTC [s]	0	0	0	7377(±427)
TI-TTC [s²]	0	0	0	4260(±252)

I.2.6 Flow- and speed-contour plots

The flow-contour plots of all four base scenarios divide the network in two parts with different flows. Downstream of the acceleration lane the flows are highest, while they are lower upstream of the acceleration lane and at the acceleration lane itself. This can be explained by the inflow of vehicles at the on-ramp.

The speed-contour plots however show a different image. Here too the plots divide the network in two parts with different flows, again different for the upstream and downstream areas. However, in this case speeds are highest in the downstream area for the low traffic intensity and congestion scenarios, but lowest in the downstream area for the medium and high traffic intensity scenarios (see Figure I.4 and Figure I.5). For the congestion scenario this is obvious since the queue moves in upstream direction. For the low traffic intensity scenario this might be caused by a slight decrease in the share of relatively slow trucks downstream of the on-ramp, since the share of trucks merging at the on-ramp is lower than the share of trucks on the motorway. For the medium and high traffic intensity scenarios, the inflow at the on-ramp apparently causes such an increase in density that the average speeds drop somewhat, although the net effect of average speeds and density is such that the flow still slightly increases downstream of the on-ramp. It must be said though that in all cases the difference in average speed between the two areas is approximately only maximum 10 km/h.

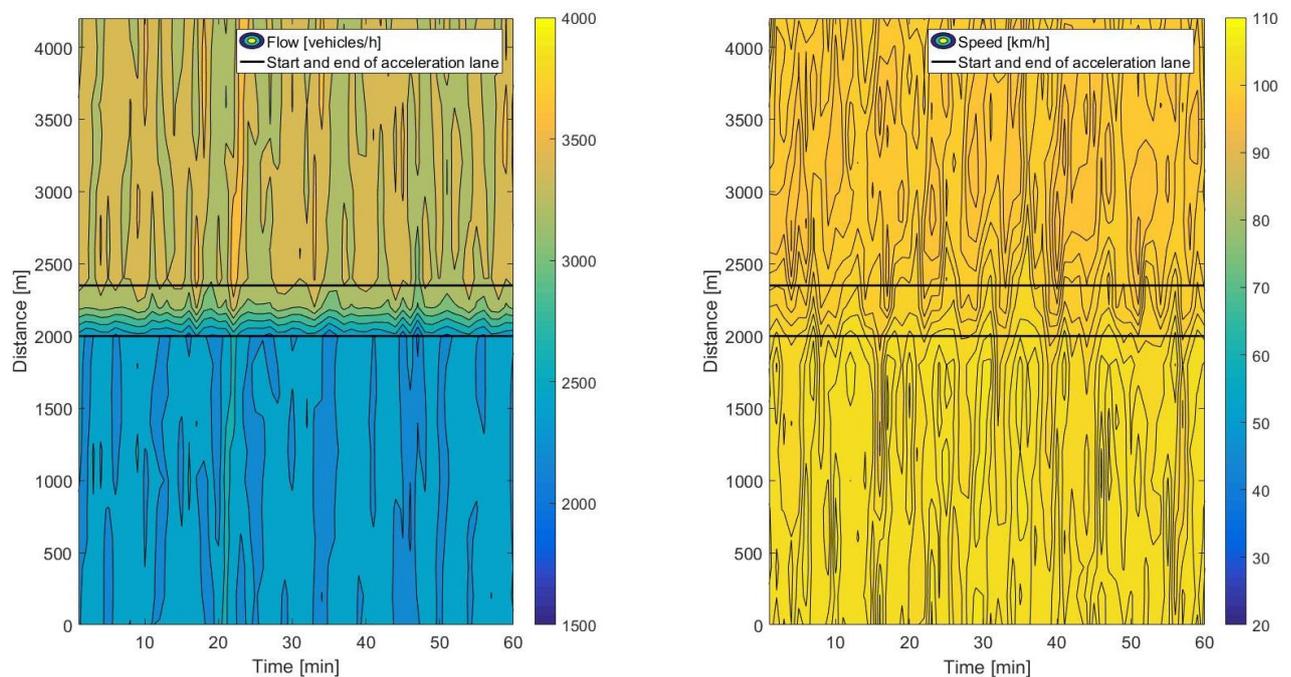


Figure I.4: Flow- and speed-contour plot of the high traffic intensity base scenario.

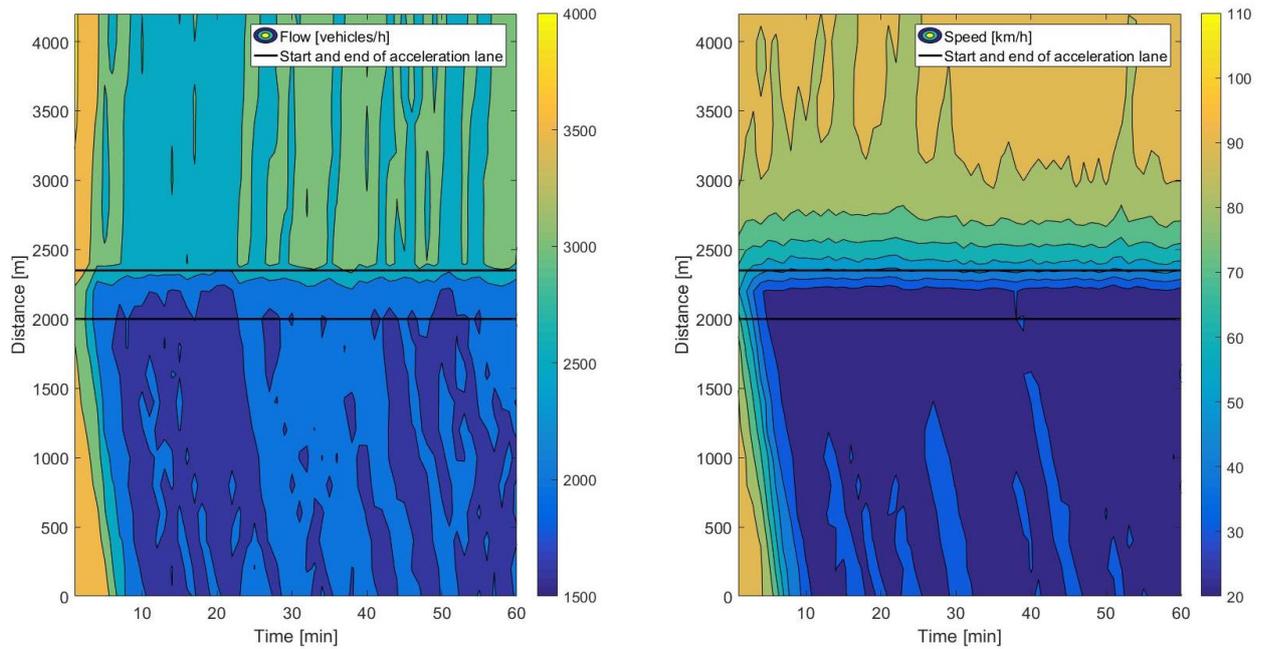


Figure I.5: Flow- and speed-contour plots of the congestion base scenario.

I.2.7 Fundamental diagrams

The patterns observed in the flow- and speed-contour plots are also observed in the fundamental diagrams. In the base scenarios without congestion, the flows and densities are highest downstream of the acceleration lane (Figure I.6). This makes sense because of the inflow of vehicles at the on-ramp. For the congestion scenario the picture is different. Here the highest flows are still observed downstream of the acceleration lane, but the highest densities occur upstream of the acceleration lane (Figure I.7). This is caused by the spillback of the queue. The free flow branch of the fundamental diagram consists merely of observations from downstream detectors, whereas the congested branch consists merely of observations from upstream detectors. This corresponds to the fact that the jam moves in upstream direction.

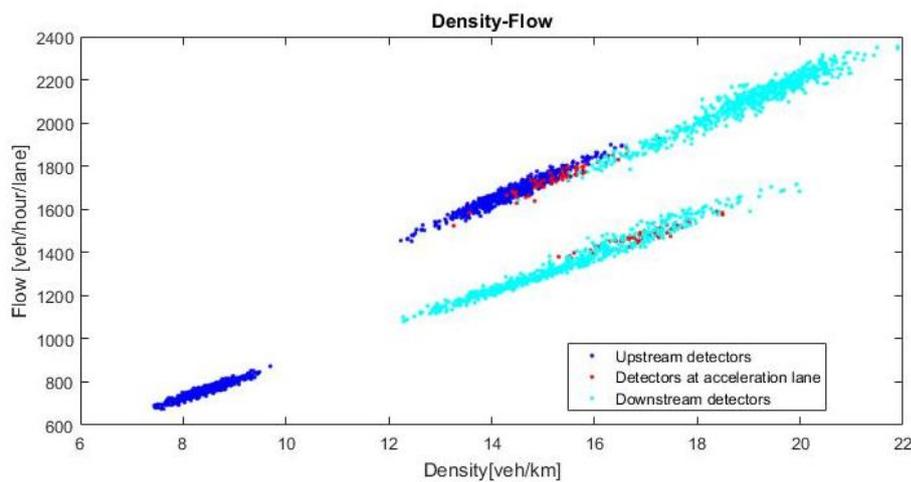


Figure I.6: Fundamental diagram of the high traffic intensity base scenario.

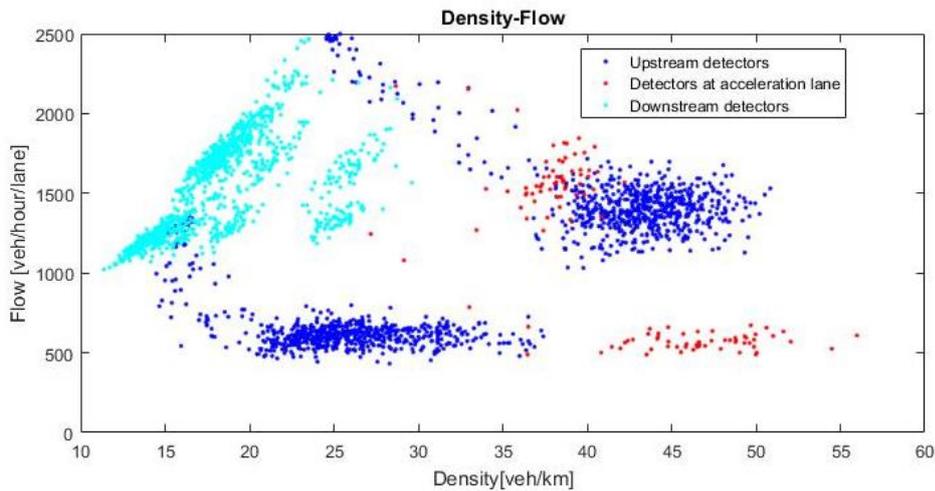


Figure I.7: Fundamental diagrams of the congestion base scenario.

In the fundamental diagrams the difference between the left and right lanes can also be observed. It is observed that for the low traffic intensity scenario the flows and densities in the right lane are higher than those of the left lane, whereas speeds are higher in the left lane. This is because the majority of traffic is in the right lane and a large share of the vehicles in the right lane consists of trucks. For the medium traffic intensity scenario the fundamental diagram already changes considerably. Now the traffic is more equally divided between the two lanes, so the difference between flows and densities between the lanes is much smaller. The speed differences between the lanes remain because there are still a lot of trucks in the right lane. For the high traffic intensity, the flows and densities in the left lane are now highest on average (Figure I.8). This is because now the majority of traffic is in the left lane. Speed differences between the lanes still remain. In the congestion scenario this speed difference becomes much smaller, both in congestion and in free flow (Figure I.9). This is because now the traffic intensity has reached capacity and speeds never exceed approximately 100 km/h anymore.

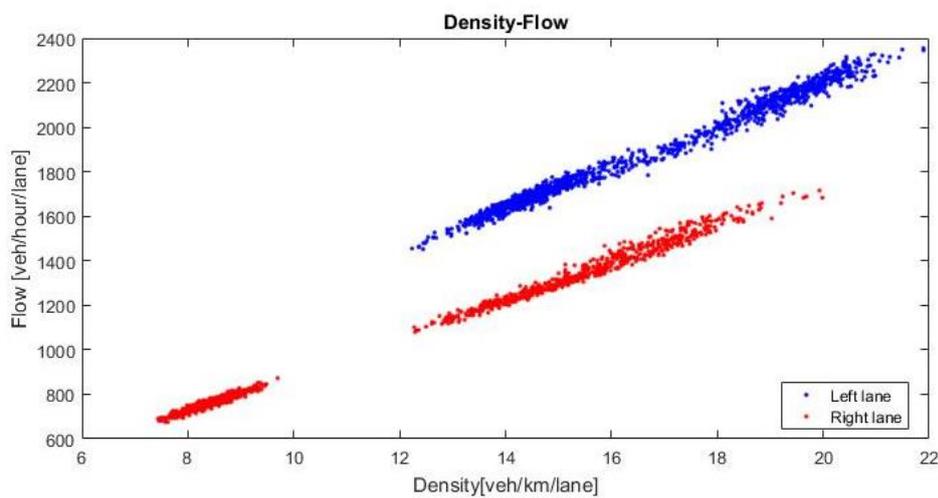


Figure I.8: Fundamental diagrams - left vs. right lane - high traffic intensity base scenario.

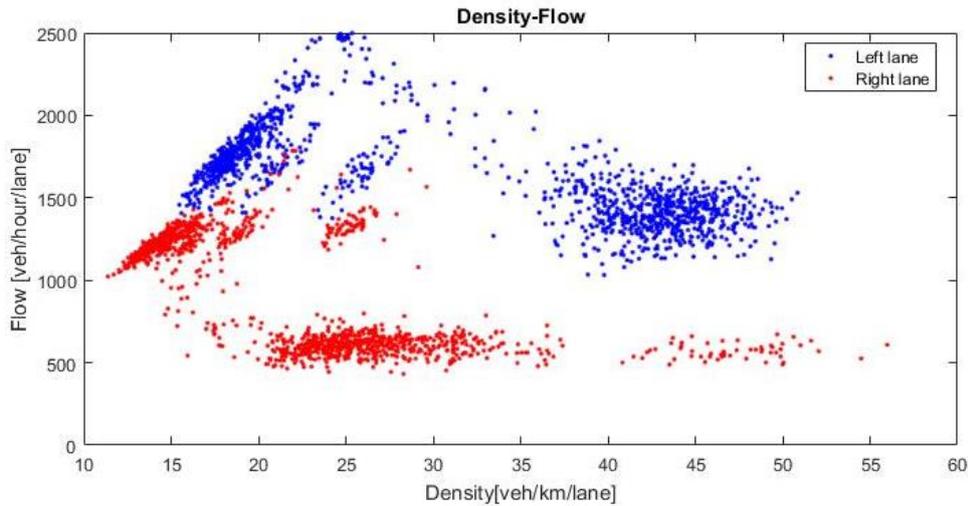


Figure I.9: Fundamental diagrams - left vs. right lane - congestion base scenario.

I.3 Conclusions

Considering the merging behaviour, the merge location is shifted towards the end of the acceleration lane during congestion whereas during free flow most vehicles merge much earlier. In none of the scenarios vehicles are unable to merge in time. The merging speed does not change a lot with the location on the acceleration lane, although it is obviously much lower during congestion. Only during congestion TTCs occur that can be qualified as dangerous, caused by shockwave propagation, although no collisions occur. In case that there is no congestion, the maximum outflow observed is approximately 15% higher than the total inflow. During congestion however, the maximum outflow is limited to the queue discharge rate of the jam, indicating a capacity drop caused by congestion. The observed queue discharge rate is lower than the capacity of the road. The difference in average vehicle speed, flow and density between the left and right lane decreases with higher traffic intensity. The findings are in line with empirical evidence and confirm the validity of the simulation model (see section 3.4 and **Appendix D**).

Appendix J

Platoon compositions

