Automated truck platoon model development and effect study of the lane change location on different motorway road sections

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Colophon

This thesis is the result of the graduation research of F.L. Hamers for a Master of Science degree in Civil Engineering at the Delft University of Technology. It is created with support of the Delft University of Technology and TNO.

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Preface

This research is the final fulfilment for obtaining the Master of Science degree in Civil engineering – track Transport and Planning at the TU Delft University of technology. The research is conducted in association with TNO.

I would like to thank all the people that contributed to this research. First of all, I would like to thank Ir. Gerdien Klunder, who was there almost every day to discuss new insights and obstacles. Moreover, I would like to express my gratitude to my daily supervisors at the TU Delft, Dr. Simeon Calvert and Dr. Meng Wang. They helped me out with structuring my work and were always able to give me a push in the right direction, even at times where I did not know what the right direction could possibly be. The difficulty of this task cannot be underestimated because my writing was often extremely chaotic. Furthermore, I would like to thank Prof. Bart van Arem and Dr. Riender Happee for their time reading my work and giving valuable insights during our official meetings. I would like to thank Dr. Maria Salomons, Dr. Jeroen Ploeg, Ir. Lucie Schotman because their algorithms made sure I did not have to start from scratch when developing a model. I also would like to thank my mother who has spent over 20 hours reviewing my use of the English language. Finally, I would like to thank all my colleagues at TNO for their support and interest in the subject and I of course also thank my family for their support and taking over different household tasks when I was unable do them due to high time pressure!

Hopefully this research can help facilitate the safe introduction of automated truck platoons and inspire other students, researchers or anybody interested to also invest their time into the effects that automated transport will have on our society.

Paco Hamers

Den Haag, September 2018

Summary

Introduction & Problem description

An automated truck platoon (ATP) is a string of trucks in which the leader drivers manual and the followers use automated and communicative car-following systems. If followers are equipped with automated car-following systems that include collision safety, ATPs could reach time headways as low as 0,3 seconds.

The upsides of ATPs over conventional driving are (1) fuel preservation due to the reduced air drag that is a result of the small time-headway and (2) reduced man hours. Due to the automated systems in the vehicles of the followers, the following vehicles do not need a human driver. These upsides form a good business case for the logistics sector.

To gain knowledge about automated truck platoons two types of studies were conducted: experimental studies and simulation studies. Most of the experimental studies focus on estimating fuel reductions. These result in estimations between 6.5% and 21% for the follower, based on the headway of the follower and the type of truck. Above mentioned experimental studies result in the scientific knowledge about fuel consumption being near top-level, on other aspects, such as 'traffic flow impact' and 'road usage', less knowledge is available. Most of what is available on 'traffic flow impact' and 'road usage' has been found using simulation studies.

Of these two topics 'traffic flow impact' has gained most attention. On a straight roadway without intersections or ramps different researches show a capacity increase. However, research reviewing road sections that include ramps do not confirm an increase in capacity but do show an increase in flowrate. Next to this, studies contradict each other in whether the introduction of ATPs will result in an increase or decrease of average vehicle velocity. On the topic of road usage, studies conclude that many conventional vehicles are unable to make a merge from an on-ramp when confronted with ATPs. This can be partially mitigated if the ATPs use different yielding strategies, such as disconnecting before a ramp.

However, considering that disconnecting and reconnecting both require so much time that during the manoeuvre between 700-1300 meters have been passed by the ATPs. A yielding strategy that includes disconnecting and reconnecting is not feasible on Dutch Motorways, because the motorway contains sections with inter-ramp distances of 1500 meters.

In this research part of the knowledge gap regarding road usage is addressed. This is done by developing a model to simulate the effect automated truck platoons have on mandatory lane change locations on the motorways and researching this effect. To accomplish this the following questions is answered:

1. Which driving models are suitable for conventional traffic, considering the interaction with automated vehicles?
2. Which known driving / control algorithms (sub models) are suitable to model ATPs?
3. How can driving / control algorithms form a full range ATP control model?
4. In which road sections is an effect expected on lane change location due to the presence of ATPs?
5. How do lane change locations differ due to the presence of ATPs?

Approach

Due to availability of software and support the simulation software that functions as a start for the simulation model is VISSIM. Question one is answered by doing a literature review into naturalistic driver models. This review focuses on inventorying the different core ideas that were the basis of creation for different car-following and lane changing models. Next to inventory of ideas, a research is done into the models which are used inside the VISSIM package. The answers are used to assess the quality and validity of VISSIM. The second question will also be answered by literature review and the answers are used as a starting point to create an Automated Truck Platoon Control Model (ATPCM).

The third question is answered by design, a choice or choices for the core of the platooning control algorithm is made based on the answer of question two and question three are answered by creating a practical full range ATPCM that is functional to measure the effect on lane change locations. To answer question four, an analysis is done on the different road sections that are present on the Dutch motorway. In this analysis, almost all different road sections are reviewed and the tactical operations regarding mandatory lane changes that the road demands of all vehicles and specifically of ATPs are collected. The answer of question four is used as a basis for the scenario design of the model.

The last question is answered by simulating the different tactical operation related to mandatory lane changing that were found while answering question four. The lane change location is measured as the distance between the first possible point to make a lane change and the point at which a vehicle accesses the line between the two lanes.

Model development

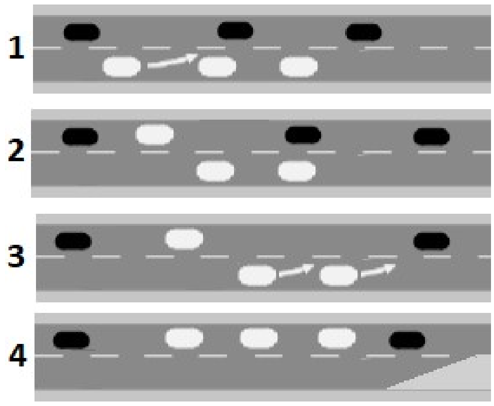
On the models in VISSIM, the car-following model in VISSIM is based on Wiedemann's psycho-physical model. This model simulates the different decision states that a human driver would go through when following another vehicle. The origin of the lateral model is based on a design of Wiedemann and Reiter. However, this model is very basic and does not incorporate the process that a human driver goes through when making lane changing decisions and manoeuvres. In an attempt to create a better lane change model different features have been added(on), such as yielding for vehicles that have a mandatory lane change into the lane of the subject vehicle and synchronisation of a subject vehicle to match the velocity of his predecessor in the target lane. These adjustments improved the lane change model but are still far from a realistic imitation of human behaviour.

On the interaction of the driver models in VISSIM with ATPs, it is expected that vehicles will merge into smaller gaps and will have a lower velocity on the acceleration lane. Lowering the velocity on the acceleration lane is applied in the models. However, lowering the critical gap of conventional vehicles when interaction with ATP is not possible unless the critical gap is also lowered when conventional vehicles interact with other conventional vehicles. Therefore, it is chosen not to make any changes to the critical gap size.

To model ATPs different models must be selected, models to simulate the longitudinal and lateral behaviour of the platoon leader and models to simulate the followers. For the longitudinal behaviour of the leader the Wiedemann longitudinal model has been selected, because the leader should mimic human behaviour. For the followers the CACC design of Ploeg *et al.* is chosen because it uses the desired velocity of the predecessor as input parameter of the model, this is quite rare because most CACC controller use the desired acceleration of the predecessor. The choice for Ploeg's design is due to the desired velocity being easily calculated in a simulation environment whereas the desired acceleration is not. Most CACC controllers use the desired acceleration of the predecessor because it can be easily estimated in real life by measuring how far the gas pedal is pushed in.

This CACC design does not guaranty collision safety. However, some basic car-following models have been used as anti-collision controllers in the past. Therefore, in this research part of the Wiedemann longitudinal model is used as a collision avoidance system. The ATP control model is designed in such a way that the followers will use CACC in car-following situations and use the Wiedemann model to do heavy braking. The braking regime will start whenever the Wiedemann model suggests a braking action with lower acceleration than -2,5 m/s^2.

For lateral control of the ATPs three distinct categories must be addressed: (1) the lateral movement (2), the lane change decisions for a platoon as a whole and (3) lane change decision for a single vehicle. The lateral movement of each vehicle is adopted from the default in VISSIM. The lane change decision for the platoon as a whole is managed by the leader of the platoon. Equal to reality, in the model, the lane change decision for the platoon is managed by the leader of the platoon. The lane change decision of a single vehicle is based on the ATP lateral model which is designed in this research. The lateral model will cause a platoon to merge as is illustrated in Summary image 1.



Summary image 1 Merging of a (white) ATP in four steps as designed in this research

Lane change locations study results

To deduce the tactics required of ATPs, the road sections on the Dutch highway that contain a possibility for mandatory lane changes are inspected. For each road section the possible conflicts are determined. For each of these conflicts the required tactic for an ATP is identified.

ATPs need to be able to execute the following tactics:

- Facilitate a mandatory predictable lane change from the right and left.
- Facilitate a mandatory unpredictable lane change from the right and left.
- Make a simple lane change to the right.
- Make a mandatory conflicted lane change to the right and to the left.
- Make mandatory weaving manoeuvre to the right and to the left.

During these tactics there is interaction with the lane change manoeuvres of other vehicles and those of ATPs. Therefore, they could conflict one another, the manoeuvres with most apparent conflicts are as follows, the section in which the tactic is present in its most isolated form is given in brackets behind it:

- Facilitate a mandatory predictable lane change (on-ramp)
- Facilitate a mandatory unpredictable lane change (off-ramp)
- Make a mandatory conflicted lane change (on-ramp)

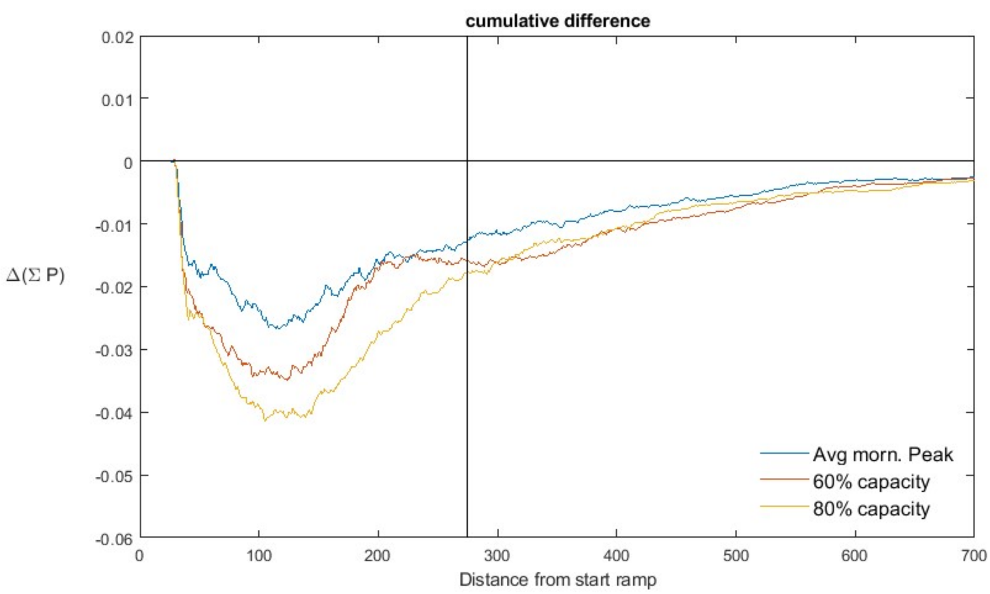
The sections in which these conflicts become most apparent are:

- Onramps and off-ramps
- Joining and splitting carriageways
- Weaving areas

To simulate the impact of the tactics two on-ramp cases and one off-ramp case has to be simulated. input data on truck share and demand is based on real world road sections and are chosen from the main corridors between the Port of Rotterdam and Belgium / Germany.

To verify the models the base case scenarios (without any ATPs) are compared to an empirical analysis of the lane change location distributions found on the Dutch motorway. With a truck share like the empirical data the base case of the simulation is good in the region between 100 and 200 meters on the acceleration lane. After that the model always gives an overestimation of the merge locations. If the truck share is much higher than in empirical data, the merge distribution shows that the model estimates merges further downstream on the acceleration lane. This is to be expected.

The first network design is of an on-ramp. The design mimics ATPs blocking off conventional traffic from merging into the main carriageway. This simulates the 'facilitate a mandatory predictable lane change' tactic. The cumulative curves of the lane change distributions are presented in Summary image 2.

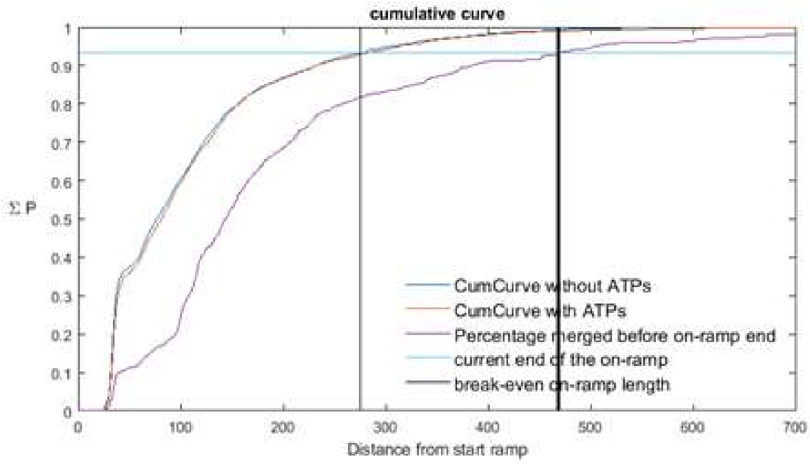


Summary image 2 Results on facilitating a mandatory lane change

The results of the scenarios including ATPs show that the platoons cause that 1-2% more vehicles are unable to make the end of the ramp. This means that in a crowded morning peak, one in every 25 vehicles requires more distance to change lanes of which half of them requires more length than the on-ramp offers.

If, equal to the base case, 10% of the vehicles can still make the ramp due to high acceleration or breaking heavily, the model predicts that during a crowded morning peak the negative effects of ATPs on lane changes can be negated by increasing the length of the merging area by about 20 meters.

The second design lane is also an on-ramp. The design mimics ATPs merging from the acceleration lane into the main carriageway. This simulates the 'Make a mandatory conflicted lane change' tactic. the cumulative curve of the average morning peak scenario is shown in Summary image 3. As can be seen in the graph, the cumulative curve of the ATP raises much slower than those of the conventional vehicles. Based on the road demand, between 18% and 28% of the ATP vehicles in unable to merge. To negate this issue, the model calculates a required acceleration lane of between 415 m and 470 m.



Summary image 3 Results of ATPs merging

The third network design is of an off-ramp. The design mimics ATPs blocking off conventional traffic from lane changing towards the off-ramp. This simulates the tactic 'facilitate a mandatory unpredictable lane change'. The results of this simulation show that most vehicles merge almost immediately after the appearance of the off-ramp. This is because for 1600 meters before the start of the off-ramp, vehicles will already have only mandatory lane changes to the right and ignore any chance to overtake. The results therefore show that all vehicles change lanes very quickly and there is no influence by ATPs.

Discussion

As any model, the applied model does not come without its limitations. For the driver model the Wiedemann car-following model is used combined with a much less validated and well described lateral model. When reviewing the lateral model, one can conclude that it is very far from human cognation and behaviour. The cause for this most likely is that a human has a gap selection process that takes much more time than a single simulation step, whereas simulations almost always decide for a single timestep based on data available in that single timestep. Because of this limitation the amount of time and distance a vehicle requires to make a merging manoeuvre is much longer in simulation. This either causes vehicles to stop at the end of the on-ramp or be deleted from the simulation at the end of the on-ramp. Neither of those options are suitable to measure how lane change locations change if an increase is expected. Therefore, removing the end of the on-ramp and making it as long as possible seems the only way to go.

This however weakens the lateral model even more, because it normally changes behaviour based on the distance until the end of the on-ramp. Results of the effect study, therefore, quite clearly show unrealistic behaviour for the base case for any data gathered passed $200m$ on the acceleration lane. However, both the simulation and the human driver make their decisions based on the gap size and the frequency of gap presentence. Therefore, the results are valuable as an indication for increased / decreased length for road sections that demand many tactics regarding mandatory lane changes. The results also can give an estimation on a break-even point, however, the uncertainty in how actual human behaviour will change this break-even point is quite large.

A second limitation of the lateral model is a strict separation between mandatory and discretionary lane changes. This causes the outcome the facilitation of unpredictable merges to be less unpredictable as one might expect in real life. However, if one assumes that a driver would be more cautious or less aggressive when encountering ATPs for the first time, the outcomes of the simulation of the off-ramp can be very realistic. However, there is uncertainty on whether these results will stay valid as drivers get more used to the interaction with ATPs. This should not be of mayor concern, though, because if drivers slowly get more aggressive towards ATPs they will do so with the current off-ramp length in mind.

The CACC that is implemented in the ATPCM did not yet have extensive testing, although it has been used in different TNO projects and still undergoes development. This creates uncertainty on the validity of the calibration settings of the CACC model. For this research that is not a large issue, because cut-ins do not exist inside the simulation, so the exact difference between the trucks within the ATP do not influence results.

The combination of this specific CACC algorithm in combination with Wiedemann as collision avoidance algorithm is a novelty. In this research heavy braking actions are extremely rare and thus such a validation of this novelty is not required because results will not be heavily influenced by changes. If one would use this model to research scenarios in which many braking actions are expected, the collision avoidance must be defined in a different manner.

The ATPCM has been designed in a manner that would make adding features easy. The main reason for this was to be able to implement lessons learned during development without having to do large parts of the programming over again. The result is an ATPCM in which different control regimes can be activated based on action lines and driver states. This causes the model to be widely applicable for different CACC purposes, also those that do not contain trucks. However, the way the collision avoidance is implemented results in the applicability of the ATPCM only on roads on which the average velocity is over 70 km/h.

Conclusion

On on-ramps, ATPs create a barrier between the merging traffic and the target carriageway. This causes the merge locations to shift further to the end of the on-ramp. It is estimated that if a platoon blocks the on-ramp, a vehicle needs up to 300 meters to get around the platoon, note that these 300 meters is an upper boundary and it is possible that the effect of platoons is smaller.

On off-ramps, no negative effects of ATPs have been found for regular traffic. In case the off-ramp is part of an intersection, it is possible that the platoon will take the off-ramp in formation. The distance a platoon needs for this is not estimated, but it is assumed to be smaller than the distance a platoon needs for a conflicted lane change. Therefore, this distance is smaller than 400 meters. In case off-ramps are designed to be taken by ATPs, the lane change section should be reviewed.

On joining carriageways, the possibility occurs that an ATP needs to make a conflicted lane change to get back into the rightmost lane. Given that it is estimated to take 400 meters per lane to make such a manoeuvre joining carriageways must be reviewed to make sure that a truck that is a member of a platoon is still able to reach all possible directions. E.g. an off-ramp cannot be 600 meters downstream of a 2x2 joining carriageway.

On carriageways splits, carriageways splits are designed with blocked markings appearing about 150 meters before the split. Given that a platoon needs much longer to perform a lane change this design guideline does not give the other road users sufficient information when they must interact with an ATP. Therefore, it is advised to change this guideline to 400 meters.

On weaving areas, the conflicts that occur in a weaving area usually contain a combination of two tactics, this makes the estimation of the distance an ATP needs to accomplish its own tactic while giving sufficient space for another to perform a tactic difficult. Where the upper boundary of the length a platoon needs is 400 meters, the interaction with other lane changing vehicles can increase this. Because the extend of the over estimation is unknown and the penalty on the interaction is unknown, the lane change distance in weaving areas remains unknown. With a rough estimation being somewhere around 400 meters.

A possible path for further research, are the traffic impacts of ATPs using variable merge section lengths. This research would require a well validated and calibrated lane change model. But there is great value in having a good estimation on relation between merge length and ATP interaction. This will contribute greatly to a cost benefit analyses on potential adjustments to the road layout in favour of ATPs.

A different path is fine tuning the estimations for merge location distributions for different network parts, especially for weaving areas. To do this, however, a driver model is required that contains a much more sophisticated lane change model than the driver model used in this research.

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Front page is an adaptation from source: http://www.daf.co.uk/en-gb/news-and-media/news-archive/articles/global/2016/q1/22032016-ecotwin-participating-in-the-european-truck-platooning-challenge (June 2018) (the original picture is confirmed not to be under copyright)

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List of terms and abbreviations

Term	**Definition**
ACC	Adaptive cruise control
Acceleration lane	The on-ramp lane in a on-ramp road section
Adaptive cruise control	An ADAS that keeps a vehicle at a constant speed without use of the gas pedal, whenever a predecessor is in range it will smoothly adapt the velocity to that match the predecessor
ADAS	Advanced Driver Assistance System
Advanced Driver Assistance System	In-car systems that assist a driver by giving warnings or take over vehicle control. These systems rely on sensory technology
ATP	Automated truck platoon
Automated truck platoon	A string of trucks in which the leader drivers manual and the followers use automated and communicative car-following systems
CA	Collision avoidance
CACC	Communicative Adaptive cruise control
Car-following (as behaviour)	The behaviour of a vehicle when trailing another vehicle
Car-following (as state)	The state in the Wiedemann model where a vehicle is trailing another while doing no ‘conscious intervention’
Carriageway	Strip of a road section dedicated to a destination
CC	Cruise Control
Collision avoidance	An ADAS that prevents collisions due to heavy breaking of the predecessor by taking over longitudinal control of the vehicle
Communicative Adaptive cruise control	ACC with communication added for quicker response
Control model	A model which determines the behaviour of a single vehicle in the traffic simulation

Term	Definition
Conventional driving	Manual driving, without automated or communicative systems
Conventional vehicles	Vehicles that are manually driven, without any automated or communicative systems
Critical gap	The smallest gap in which a certain vehicle is willing to merge into
Cruise Control	An ADAS Drive assistance system that keeps a vehicle at a constant speed without use of the gas pedal
Distance-headway	The distance between the front of the vehicle and the front of the predecessor
Driver model	A control model that models human driving behaviour
FRACC	Full range ACC
Full range ACC	ACC with a collision avoidance system added
Headway	See time-headway
Lane	A strip of roadway for a single line of vehicles
Lane change location	The spatial point on a carriageway where the front of a vehicle crosses the line while changing lanes
Lane change location distribution	The distribution of all lane changes between two lanes on a certain road segment
Motorway	A road type designed for high speed traffic containing no crossings. Entries and exits are designed with ramps and intersections are a series of splitting and merging roadways
Road segment	A longitudinal segment of a roadway or (combination of) carriageway(s)
Roadway	Part of a road used by traffic
Tactic (lane change related ...)	The preparation and initiation required of a vehicle due to an intended lane change of the vehicle itself or a vehicle around it
Time-headway	The time required for a vehicle to reach the position of its predecessor
TP	See truck platoon
Truck platoon	A string of trucks trailing a leader

1. Introduction

An automated truck platoon (ATP) is a string of automated trucks, of which the first vehicle is the leader and the rest are followers. The leader drives manually or with adaptive cruise control (ACC). The followers use either fully automated car-following systems or driver assistive systems to create a stable time headway. Most commonly the followers are equipped with a cooperative ACC (CACC) system, combined with additional driver assistive systems for lane keeping and lane changing. If followers are equipped with automated car-following systems that include collision safety, ATPs could reach time headways as low as 0.3 seconds. [2]

The upsides of ATPs over conventional driving are (1) fuel preservation due to the reduced air drag that is a result of the small time-headway and (2) reduced man hours. Due to the automated systems in the vehicles of the followers, these vehicles do not need a human driver. These upsides are reason for the European union, the Swedish, German and Spanish governments and parties such as Ricardo, Volvo and different research institutes to fund research projects such as SARTRE to investigate the possibilities for implementation [3][1]*, [2].

1.2. Problem description

As the expected launch date of commercial ATPs comes closer [4]*, the urgency of having knowledge about the effects of ATPs increases. In an attempt to gain knowledge about ATPs two types of studies were conducted: experimental studies and simulation studies [5]. Using experimental studies, the scientific knowledge about fuel consumption is near top-level, however on other aspects, such as 'traffic flow impact' and 'road usage', less research has been done [6].

The experimental studies on fuel consumption result in estimated fuel savings between 6.5% and 21% for the follower. The variance is based on the headway of the follower and the type of truck [7], [8]*, [9], [10], [11], [12].

The amount of simulation studies is limited, most of them are evaluating the traffic flow impacts. Müller [13] found a capacity increase of 5.5% based on the interaction between the Wiedemann model and CACC on a three-lane motorway with no ramps. Equal to Müller, Deng [14], also simulated an interaction between the Wiedemann model and CACC on a motorway situation without ramps and also found increased capacity. Next to that, Deng concluded that the increased capacity was at the expense of slight speed reductions.

Ramezani et al. [5] was the first to combine an experimental study with a simulation study. In the experimental study the trajectories of trucks following each other using CACC where gathered to create a calibration data set for the design of a truck platoon control model (TPCM). This TPCM can mimic the behaviour of a follower in ATP that uses CACC as main car-following method and human interference to ensure collision free driving. The simulation study was based on the interaction of this calibrated TPDM with a Gipps model in a corridor containing ramps. Ramezani et al. found that the CACC would increase flow rate and, in contrary to Deng [14], concluded that the trucks would have a slight increased traffic speed in uncongested road sections.

[1] A source indicated with an * is non-scientific source meaning it is **not** a: journal article, conference proceeding, Ph. D dissertation or (parts of a) scientific book / report.

Van Maarseveen [15][2]** also did a simulation study on ATPs in a section containing ramps. His focus was primarily on three different tactics that an ATP could use to facilitate merging near on-ramps. He simulated interaction between the Full Range CACC. This control model is an extension on the full range ACC of [16] et al. [16] with the longitudinal IDM+ and LMRS [17] as lane change model. Maarseveen is the first to model ATPs assuming a collision avoidance algorithm instead of using human interference as collision safety. His model was able to simulate time headways of followers as low as 0.3 seconds. Van Maarseveen concludes that on-ramp vehicles are increasingly unable to merge at increasing intensities and penetration rates of the full range CACC trucks. However, if followers in an ATP are allowed to create gaps for merging vehicles the merging problems are solved.

Bergenhem et al. [18] did a sub-micro simulation that is different from the more traditional driver models because it focuses more on interaction between the vehicle, the driver and the road instead of focusing on the interaction between vehicles. The simulation tool PELOPS has been used to make estimations on the time it takes to complete a connection to a platoon or a disconnection from a platoon. The distance headways for the followers in a platoon has been set to 5 meters and 10 meters at a velocity between 80-90 km/h. This results into a time headway between 0.2-0.4 seconds for the followers in the platoon. The results of Bergenhem et al. are presented in Table 1. Their results show that a connecting or disconnecting manoeuvre often takes more than a kilometre to complete.

Table 1 Results of Bergenhem et al. (adaptation from Bergenhem et al. [18])

	(dis)connect duration		**(dis)connect distance; estimated at 80 km/h**	
Platoon headway:	**10 m**	**5 m**	**10 m**	**5 m**
Join from behind	45 s	48 s	1000 m	1067 m
Join from side	24 s	75 s	533 m	1667 m
Join from front	47 s	55 s	1044 m	1222 m
Leave from behind	53 s	57 s	1178 m	1267 m
Leave from side	32 s	55 s	711 m	1222 m
Leave from front	57 s	60 s	1267 m	1333 m

When reviewing the available knowledge and applying it to the Dutch situation, it can be noted that in the Netherlands ramps are often close to each other, for example on the A20 and the A15 there are segments with more than 3 ramps in a section of 5 kilometres. Although Van Maarseveen suggests that if followers in an ATP are allowed to disconnect to create a gap, the disconnecting and reconnecting would take longer than reaching the next ramp according to Bergenhem et al. This implies that on sections with many ramps either vehicles near on-ramps cannot merge in time due to ATPs "blocking" them off from the main carriageway or ATPs are unable to keep platooning formations.

Apart from the problem stated above, one can also note that so far only attention has been given to sections containing on-ramps. With one exception being Ramezani et al., they also included

[2] A source indicated with ** is master thesis

off-ramps. This means that there is still a large knowledge gap for any other section that includes any kind of merging behaviour or other lane change related tactic.

1.3. Research formulation

The aim of this research is to give insight into how long merging and weaving areas should be to facilitate safe merging in mixed traffic. Mixed traffic in this research is defined as traffic containing conventional traffic (passenger cars and trucks) and ATPs.

The location at which vehicles make lane changes in different infrastructural situations is researched using a simulation study. To research interaction between conventional vehicles and ATPs within a simulation, a control model for ATPs is requires as well as a driving model to simulate the behaviour of the conventional vehicles. Next to that a network design is required. The network design is based on lane change related tactics that the Dutch motorway network requires of ATPs.

The goal of this research is to ***develop a model to simulate the effect automated truck platoons have on mandatory lane change locations on the motorways***. To structure the research the following research questions are formulated:

1. Which driving models are suitable for conventional traffic, considering the interaction with automated vehicles?
2. Which known driving / control algorithms (sub models) are suitable to model ATPs?
3. How can driving / control algorithms form a full range ATP control model?
4. In which road sections is an effect expected on lane change location due to the presence of ATPs?
5. How do lane change locations differ due to the presence of ATPs?

1.4. Approach

To reach the goal, the research questions are attempted to be answered as follows.

To answer the first research question: 'Which driving models are suitable for conventional traffic, considering the interaction with automated vehicles?', a literature review is done on naturalistic driving models and conclusions are drawn on the applicability of the models towards interaction with automated vehicles. This is presented in chapter *2 Human behaviour driver models*. The conclusions of this question are used to review the used software package on applicability for modelling the integration of conventional vehicles with ATPs. This is described in paragraph 3.3.

As a means of answering question 2, 'Which known driving / control algorithms (sub models) are suitable to model ATPs?' The simulation studies regarding platooning or automated / assisted car-following algorithms are reviewed. The answers to this question are used as input for question 3 and this is presented in paragraph 4.1.

To answer the third question: 'How can driving / control algorithms form a full range ATP control model?' The collected ATP models are checked for implementation in the used software package. This mainly depends on whether the input parameters of the model can be calculated within the software Also, if combinations of models are required, a practical approach is taken with focus on optimal behaviour for the research case. The answers of the second and third research question are combined to form the basis of the ATP control model design. This is presented in chapter *4 Automated truck platoon control* model.

To answer question 4, ‘In which road sections is an effect expected on lane change location due to the presence of ATPs?’, an analysis is done of the main truck corridors between the Port of Rotterdam and Belgium / Germany. These corridors have the highest potential for ATPs to debut in [2]. Based on the analyses, the tactics that the road layout requires of vehicles / drivers to solve are listed. From these tactics only, those that might be influenced by ATPs are considered. From those, a road section is selected in which a tactic is present in its most isolate form. The selected road sections will form the basis of the network design used in the simulation model. This is presented in paragraph 5.1. For each selected road section, a real-world road section is chosen, this real-world road sections is used for input data on truck share and demand. The real-world road sections are chosen from the main corridors the Port of Rotterdam and Belgium / Germany. This is presented in 5.2.

As a means to answer Question 5, ‘How do lane change locations differ due to the presence of ATPs?’, morning peak simulations are run on the road sections from the answer of question 4. These simulations will give insight in the effect of ATPs have when the road layout demands a certain tactic of the vehicles in that road section. By extrapolating the effect of a tactic to all sections in which that tactic is required, one can conclude on a variety of road sections based on a few simulations.

Each scenario is run ten times for the base case without ATPs and ten times with ATP. This time slot is chosen due to its high intensity and the availability of data on this timeslot. To gain insights in future effects, also increased road demands are modelled. Therefore, scenarios with 60% of road capacity and 80% of road capacity is also simulated. During these future effect scenarios, the truck share and share between different carriageways will stay equal. The scenario design is presented in 5.3 and 5.4.

The trajectory data of the simulation is retrieved, this is used to calculate the exact location at which all vehicles cross the line between two carriageways. The difference between the lane change location of the base case and the ATP case is used to quantify the effect of the presence of ATPs. A visualisation of the simulation and the data extraction is presented 5.5 and the results are presented in chapter 6. To be able to indicate the value of the results, the precision of the model is analysed, and the model is verified on empirical on-ramp data. This is presented in paragraph 5.6 and 5.7.

The software package used for the simulation is VISSIM. This software package is chosen for two reasons. The first reason is that VISSIM has different viable options to develop a dedicated model using an advanced programming interface. This offers a versatile environment to implement automated vehicles. The second reason is that the author has access to direct support for VISSIM, this is not the case for the other software packages. Note that the choice for VISSIM was not based on the quality of the behavioural models that are embedded in the software package. Therefore, the behavioural models used in the VISSIM software package must be analysed to be able to present the methods used transparently. This is presented in the chapter 3.

Combining the answers of question 1-4 a model can be designed conform the research goal. The answer to question 5 will give a prediction which is conform the research goal. Therefore, the research goal is met.

1.5. Scope

To reach the goal within the allotted timeframe the following limitations were imposed. Limitations that were mentioned earlier in the research goal and approach, e.g. the software package used, will not be repeated here.

For the sake of reducing the complexity when creating an ATP control model (ATPCM), an ATP is modelled here as a platoon of three vehicles in which the leader drives manually and the other two vehicles automatically follow. The reason not to consider longer platoons is because each new vehicle in the platoon results in a whole new set of rules in the ATPCM. This is especially a problem when lane changing is included in the control model. Negative effects that ATPs have with lane changing and blocking lane changes of other vehicles is expected to scale with the platoon length. This means that the choice for three vehicles is only a start in the research to the lane change effects of ATPs on the location of lane change manoeuvres.

Furthermore, a longer ATPs will result in an extra timestep of delay in transferring data between ATP vehicles inside the VISSM simulation. This has impact on the car-following and lateral behaviour of an ATP, especially for the longitudinal string stability. Since string stability becomes more important for longer ATPs, a choice for three-vehicle ATPs reduces the need for calculations on string stability.

Variation in different types of ATPs would result in a unique control model for each type, this is impossible to implement in this research due to time limitations. Therefore, this research contains one type of ATP.

The results of this research will not include traffic flow impact, in the network simulation merging areas are superficially increased to unrealistic lengths. This makes it possible to measure where vehicles would merge if they would fail to merge at conventional merging sections. This theoretical approach has an unknown positive influence on the traffic state and therefore the negative impact on traffic flow cannot be measured.

Note that in the analysis of the truck corridors only regular situations are considered. Roadworks or accidents are not in the scope of this research.

The ATPCM will contain existing algorithms as much as possible and only will have novel adaptations to solve issues regarding lack of functionality or to make combinations of algorithms possible.

1.6. Main contributions

This research is written to give insight into how long merging and weaving areas should be to facilitate safe merging in mixed traffic. It tries to do so by providing:

- A control model able to simulate the behaviour of ‘three vehicle ATPs’ in motorway conditions.
- Insights in the effect that ATPs have on infrastructure length that other vehicles require to make a lane change manoeuvre.
- Insights in the infrastructure length that a ‘three vehicle ATP’ requires making a lane change manoeuvre.

1.7. Report outline

In chapter 2 *Human behaviour driver models*, the current state of the art of driver models are presented with the aim to create enough background to assess the quality of the driver models that are included in the VISSIM software package.

In chapter 3 *Driver model in VISSIM*, the models that run inside the VISSIM software package are put apart. The main goal of this chapter is to give the reader understanding of the methods used. In this chapter, also the assessment of the driver model based on lessons learned in chapter 2 are presented.

In chapter 4 *Automated truck platoon control* model, the current state of the art of automated driving systems used for ATPs presented, and a selection is made and discussed. This selection is used to create the ATPCM for this research. This chapter also contains the design description of the ATPCM.

In chapter 5 *Simulation network design*, the choices for the simulation model design are presented and discussed. It also contains the reasoning that makes it possible to apply the outcome of three simulation designs to a whole network. This chapter also contains some verification of the models. Finally, the method data extraction is explained.

In chapter 6 *Results* of the simulation research are presented. Finally, in chapter 7 *Discussion & Conclusion*, the limitation of the model and its implications on the results are discussed followed by the conclusions, this chapter finishes with suggestions for future research.

2. Human behaviour driver models

In this chapter different kinds of behavioural models are described, the goal of this chapter is to create background to be able to assess the quality of the VISSIM software package. The breakdown of the models that are contained within VISSIM is done in chapter 3.

In an attempt to model traffic under different circumstances, many created agent-based driver models mimic human behaviour in a microscopic manner. The created models have in common that they represent the behaviour of a single vehicle. They can be characterized within three groups: Longitudinal models, Lateral models and Integrated models [19]**. The Longitudinal models describe the behaviour of a vehicle that is executed within its lane, e.g. car-following, acceleration, collision avoidance. Lateral models describe the behaviour of a vehicle with respect to its tactics on lane changing. This is often distinguished in necessary lane changing (lane changing to follow the planned route) and voluntary lane changing (lane changing to overtake). Lastly on integrated models, the integrated model is a behavioural model that includes both the lateral and longitudinal aspects in an inseparable way.

In paragraph 2.1 the longitudinal models are reviewed, a baseline of how they are designed is presented as well as the typical extensions that are added to them to create more naturalistic behaviour. In 2.2 the lateral models are explained, and some notable examples are given. The integrated models will not be included in this research.

2.1. Longitudinal models

Longitudinal models are created to mimic the behaviour of human drivers in their car-following behaviour. They assume that drivers adjust their behaviour to stimulus. As Saifuzzaman and Zheng [20] formulate it for part of the longitudinal models:

$$response = sensitivity * stimulus \qquad \text{Equation 1}$$

But as van Wageningen-Kessels et al. [21] note, almost all longitudinal models can better be described by:

$$response = f(stimuli) \qquad \text{Equation 2}$$

In which the stimuli are based on the behaviour of the leader and the current state of the own vehicle. In this paragraph the models that have been developed are explained by fitting them to the framework of Equation 2. Doing this will give a clear view on the differences between the models based on response, stimuli and shape of function f.

In the late fifties the first formulations of the function in Equation 2 were created in the form of the GHR-model [22], the safe distance[3] model [23] and Helly's model [24]. The difference of the model is mainly described by the choice for the stimulus and the shape of function f.

In the GHR-model it is assumed the speed difference between two vehicles as the main stimulus and the acceleration is the response, however some newer versions of the GHR model also include

[3] also known as collision avoidance (CA) models, however it is not always the same from CA algorithms used for emergency braking in combination with CACC. To prevent confusion safe distance models will never be referred to as CA models in this research.

headway as a stimulus. The shape of the function includes a multiplication between the stimulus and a sensitivity parameter. Although the sensitivity parameter was a constant in the original version and thus resulting in a linear shape. In newer designs of the GHR-model the sensitivity parameter has many different shapes and, in many cases, adds stimuli to the model. Therefore the GHR-model is more a family of models than an exact formulation. [20], [21], [25]

In the safe distance model, the response is velocity and the stimuli are velocity ($v_n(t)$) headway ($d_n(t)$) and velocity of the leader ($v_n(t-\tau)$) in which τ is the reaction time. Kometani and Sasaki [23] originally formulated an exponential relation between the stimulus and response. But the currently most popular version of the safe distance model is the Gipps model [26]. This model assumes a parabolic relation between the stimulus and response.

In Helly's model the response is acceleration and the model has four stimuli, being: $v_{n-1}(t-\tau)$, $v_n(t-\tau)$, $d_n(t-\tau)$, $a_n(t-\tau)$. The assumption, that the acceleration experienced by the driver is one of the inputs determining a desired headway, makes this model unique. This desired headway is used in calculating the response. The shape of Helly's model can be described as a sum of different linear functions. [20]

Apart from these early models, more models have been developed in the same format. The stimuli are often $v_{n-1}(t)$, $v_n(t-\tau)$, $d_n(t)$, but the shape for the models vary. The main differences in the models lie in the assumptions that the researchers made. More modern models that have gained a lot of attention are the Intelligent Driver Model (IDM) [27] and the Optimal Velocity Model (OVM) [28]. The IDM assumes that each driver has a desired velocity and distance towards its leader. The response is based on two fractions of actual and preferred distance / velocity. The shape of f in IDM is based on the sum of a vehicle 's specific constants combined with fractions mentioned above. OVM assumes that vehicles have an optimal velocity. This idea is close to the assumption of preferred velocity in the IDM. The difference however is that the preferred velocity in IDM is calculated by products of linear and parabolic headway and velocity functions whereas the OVM's optimal velocity is based on a hyperbolic tangent of the headway.

The above-mentioned models got criticized for lack of human psychology and assuming a driver has full information. In response for this, different efforts were undertaken to create a more humanlike approach. The different ideas to create more humanlike behaviour are described in this paragraph. Often such ideas were only implemented as an add-on to a specific model. However, often such ideas can be used for different models, therefore only the idea are described in this paragraph and the exact implementation will not be presented.[25]

One of the first ideas to mimic human behaviour better is based on the observation of Herman and Rothery [29]. They observed that the acceleration and deceleration capabilities of human drivers are not equal. Implementation of this idea into models often results in defining different driving states such a car-following and free flow. [20]

Next to lack of human psychology, one of the main critiques on the earlier models is their lack in mimicking human perception. They assume that a human has full information and perceives equal situations in different locations exactly the same. They also assume that changes in the stimulus result in equal changes in response, independent of the perception distance of the driver [30]. [25]

Wiedemann tried to tend to all the above-mentioned critiques by designing a state-based model that uses perceptual threshold that simulate the human perception. A stimulus threshold will change the driver state and thus the response function. [31] However such threshold lines between driver states will cause unhuman like switching between driver states in some cases. To prevent this, the driver states overlap and switching happens in a “fuzzy” manner [32]. A different method to prevent hard switching between states, or harsh reaction based on heavy changes in stimuli. Lee [33] introduced a memory function. This redefines Equation 2 to:

$$response = \int_{t-t_m}^{t} f(stimuli) \qquad \text{Equation 3}$$

In which t_m is time for which a memory is kept for all stimuli.

2.2. Lateral models

It is a common assumption that driver workload and stress are significantly increased during lane changes [34]. However, examining driver model reviews, one will find that longitudinal models have gained much more attention than lateral models. This causes concern on the level of detail that the models reach in mimicking human behaviour. The description of models in this paragraph form a background to compare with the lateral model of VISSIM which is described in paragraph 3.2.

Zheng separates the lateral models into two groups. The lane change decision (LCD) and the lane change impact models (LCI). The LCD models describe the decision-making process of a vehicle to make a lane change while the LCI models describe the behaviour of other vehicles that react or facilitate a lane change of someone else. First the LCD models are described followed by the LCI models.

Many of the LCD models are based on a decision flowchart containing ‘true or false’ statements, the first model in this fashion was proposed by Gipps in 1986 [35]. It was designed as an add-on to the already existing Gipps longitudinal model. The lane change model mimics the drivers’ behaviours based on necessity, desirability and possibility (safety). As an illustration, the flow chart of the original Gipps model is presented in Image 1. Using such a deterministic system caught on and many others developed models with such a format containing different assumptions. One of the more modern decision flow chart models is the MOBIL model [36], this model uses the assumption that a driver prefers to minimize his own deceleration and the deceleration of the rear vehicle in the target lane. One of the main critiques of decision flow chart models is the hard separation between mandatory and discretionary lane changes. Events in which a vehicle will overtake a truck before making its mandatory lane change do not occur when using such models.

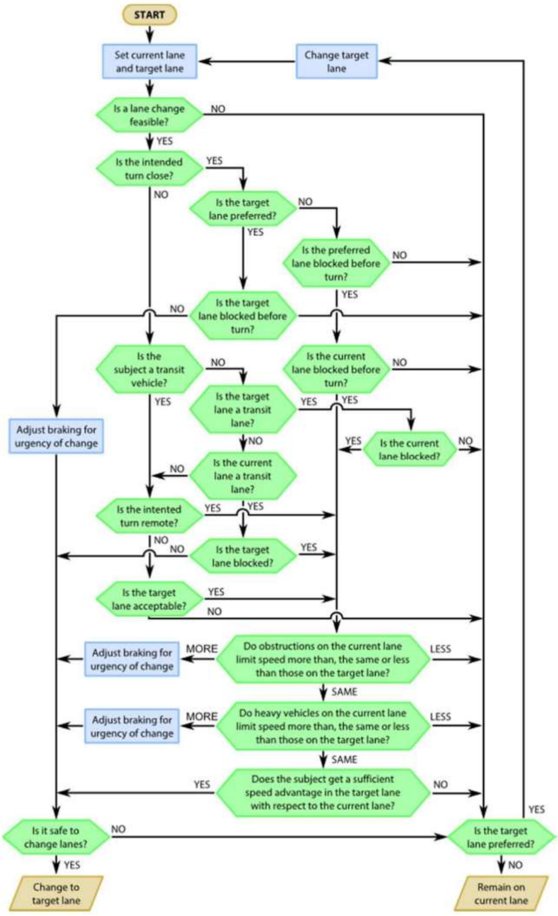


Image 1 Gipps flowchart (copy from M. Oud [19]**, adaption from Gipps[35])

Another approach to lane change models was proposed by Worrall et al. [37] in 1970. They proposed lane changes in the form of a homogeneous Markov chain. Using a Markov chain will both capture the variance of the driver population by its stochasticity but keeps the basic form like the flow chart which makes it possible to implement the similar logical structures as mentioned before.

A third approach to model lane change was first presented by Ahmed et al. [38] in 1996, they used utility based choice modelling as a basis to create a lane change model. Although using such a model would be great to solve the problem presented above regarding the hard separation between mandatory and discretionary lane changes, Ahmed et al. kept a hard separation in their model. However, in 2003 Toledo et al. [39] created a utility based lane change model that did contain a less rigid separation between mandatory and discretionary lane changes.

Hamdar et al. [40] criticized the earlier lane change models for neither sufficiently nor explicitly considering the stochasticity or potential unsafe behaviour of the human cognitive processes. Hamdar et al. proposed hazard-based functions to better simulate these cognitive processes.

When describing the LCI, Zheng [41] distinguishes three phases a follower of the target lane goes through when encountering a vehicle merging into his lane. The first phase is anticipation, which is followed by relaxation and finally regression. During anticipation the follower notices the merging vehicles intent and adjusts its behaviour. During the relaxation the follower will accept smaller headways without braking heavily and slowly will reach its desired headway. During the regression the driver characteristics change into a slightly more aggressive style. The first two phases that

Zheng describes have later been modelled by Schakel et al. [17] in their integrated Lane change Model with Relaxation and Synchronization (LMRS). Relaxation in their model is equal to relaxation as described by Zheng. Synchronization however is broader than the anticipation that Zheng described. Synchronization will let the vehicle attempting to merge adjust its velocity to the vehicles in the target lane. As well as let the vehicle in the target lane adjust their velocity to the merging vehicle.

2.3. Application of driving models to simulate interaction with automated vehicles

Van Maarseveen [15]** analysed the interaction between conventional traffic and ATPs in order evaluate whether the models require any adaptation to be able to model interaction with ATPs. Since empirical data on the interaction with ATPs and conventional traffic is rare, Van Maarseveen examined three things. Firstly the data of the European Truck platoon challenge [42], secondly the interaction between trucks and vehicles during times with high truck intensity, this is interesting because (non-automated) truck platoons will form during such a period and lastly 'Longer Heavier vehicles' LHVs. LHVs are a special type of truck that has a maximum length of 25,25 m instead 18,75 m. Van Maarseveen concluded that conventional vehicles are likely to drive more slowly on the acceleration lane and the gap acceptance will become smaller in case there is interaction with an ATP.

2.4. Conclusion

The development of driver models is not near to completion, much can still be done to get more accurate human behaviour. Given that most of the models use equal input parameters and output parameters, the novelties of one model can often also be applied to other models. This system creates an environment in which different driver model algorithms are constantly evolving.

Longitudinal models are much further developed than lateral models, this causes the models that measure lane change specific problems to be less accurate than models that only include longitudinal behaviour. However, in the last decade much improvement has been made.

3. Driver model in VISSIM

The name VISSIM comes from the abbreviation 'Verkehr Im Stadt SIMulation'. As the name suggests its main application lies in modelling urban areas. Nevertheless, it is also suitable for modelling highway purposes.

The algorithms that run in the background of VISSIM are unknown to the public. What is known is that VISSIM is based on the MISSION project of the University of Karlsruhe [43]. In this project an attempt is made to capture more human properties into driver models. However, the algorithms in VISSIM are not exact replicas of those that came from the MISSION project. According to Fellendorf and Vortisch [43], the algorithms in VISSIM are based on the psycho-physical car-following model that Wiedemann developed in 1974 [43], this also is backed up by the references made in the VISSIM 8 manual [44]*. Between 1978 and 1983, the lane changing model has been developed based on the findings of Sparmann [45], Winzer [46], Brannolte [47], and Busch and Leutzbach [48].

In this chapter an attempt is made to present the algorithms that are present in the VISSIM software package. This to review its applicability to model the interaction of automated vehicles with conventional traffic. The description of algorithms is based on observations during simulation, the VISSIM manual [44]*, and a description of the software package by Fellendorf and Vortisch. Firstly, a description is given of the longitudinal behaviour in paragraph 3.1. This is followed by a description of the lateral behaviour in 3.2.

Apart from the pure algorithmic models that represent behaviour, the software package has methods to assign and change behaviour of vehicles for example based on their location. How the assignment of behaviour works in VISSIM is explained in 3.3. Lastly, a model has little value if it does not represent the real world. Therefore in 3.4 the actions that are taken to validate VISSIM are presented.

3.1. Longitudinal behaviour

Longitudinal behaviour in VISSIM is based on different vehicle states, in longitudinal behaviour the following states can be identified: car-following, free flow, approaching, braking, 'heavy braking (collision)', 'facilitating lane change' and 'necessary lane change longitudinal behaviour'. The Wiedemann model describes the following states:

- car-following (described in 3.1.1.6)
- free flow (described in 3.1.1.7)
- approaching (described in 3.1.1.8)
- braking (described in 3.1.1.9)
- heavy braking (collision) (described in 3.1.1.9)

Which leaves the following states undescribed:

- facilitating lane change (described in 3.1.2)
- longitudinal behaviour before necessary lane changing ((described in 3.1.2)

In this sub paragraph firstly the Wiedemann model is described, followed by the knowledge about the non-Wiedemann driver states.

3.1.1. The Wiedemann model

As earlier mentioned the Wiedemann model consists of different driver states. The relation these states have towards each other is graphically presented Image 2. Note that the number represent the different states (as shown in Table 2), d is the headway and Δv is the speed difference between vehicle n and its leader $(n-1)$. The black arrow represents an example of how the relation between two vehicles could propagate over time.

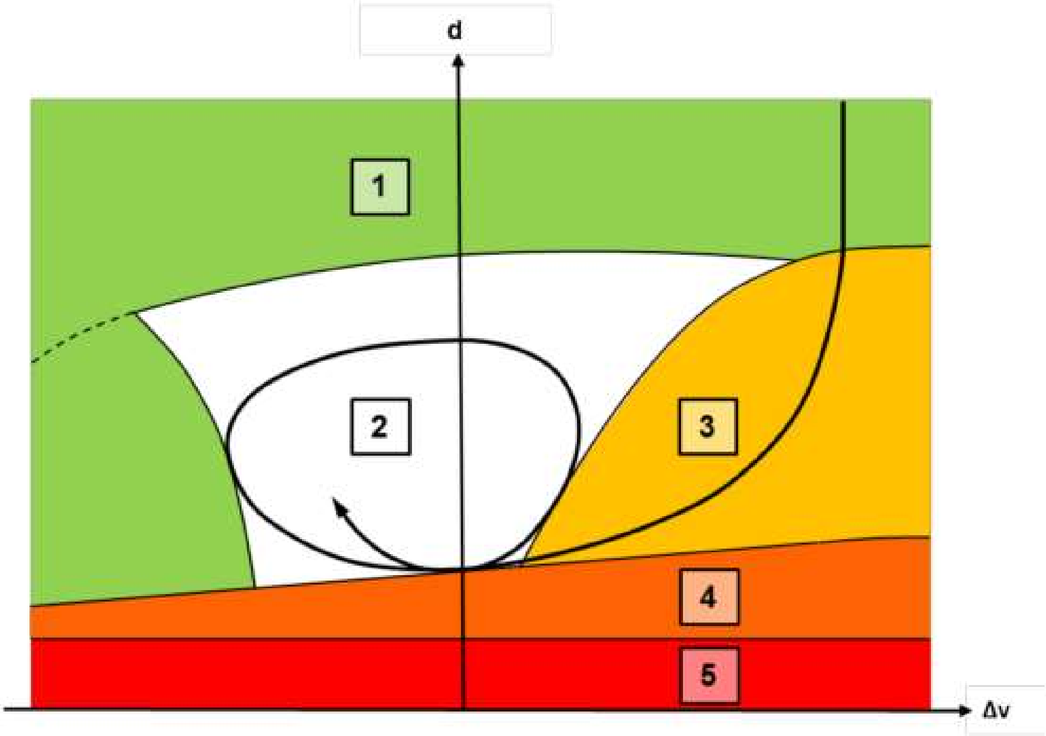


Image 2 Wiedemann model (copy from VISSIM 8 manual) [44]*

Table 2 Wiedemann Driver states

No	W. Driver state
1	Free flow
2	Car-Following
3	Approaching
4	Braking
5	Collision

Table 3 Wiedemann action point naming

zone	zone	comment	name
1	2	Top of side 2	SDX
1	2	Left side	$OPDV$
1, 2	3		SDV
1, 2, 3	4		ABX
4	5		AX

In Table 3 the naming of the actions points is given. Although the table describes lines in Image 2. The reasoning it is called a point is as follows: A vehicle will also behave as a line in the graph, and the intersection of that line with a line defined in Table 3 is an action point. At such a point the equation that creates behaviour changes. Note that the action points are different for each vehicle in the simulation, because their exact formulation is based on a random number generator. (The naming style is an adaptation from Fellendorf and Vortisch [43].)

Note that the original Wiedemann model also contained a *CLDV* border, which was slightly to the left of OPDV, and represented different behaviour if fast approaching. However, since it is not present in the VISSIM manual. It is assumed that this action point as well as the 'fast approaching regime' is unused in VISSIM.

In subparagraph 3.1.1.1 up to 3.1.1.5 the formulation of the action point lines is described. This is followed by the formulation of behaviour within each state of the Wiedemann model in sub paragraph 3.1.1.6 up to 3.1.1.9. This description is an adaptation from Wiedemann and Reiter [31] combined with Olstam and Tapani [49]. The final remarks at the end of each sub paragraph as well as the reformulation of equations is new work.

3.1.1.1. AX: The action point of the collision regime

AX is reached whenever vehicle n is so close to its leader that it goes into a collision avoidance state. AX is defined as a constant distance headway independent of relative velocity. The formulation is:

$$AX(n) := L_{n-1} + AXadd + RND1_n * AXmult \qquad \text{Equation 4}$$

Where L_{n-1} is the length of the leader, $AXadd$ is a baseline safety distance for all vehicles, $RND1_n$ is a vehicle dependent random number of distribution N(0.5,0.15), and $AXmult$ therefore creates a vehicle dependent safety distance. Note that AX is independent of the relative velocity and therefore should be represented as a straight line in Image 2.

3.1.1.2. ABX: The action point of the braking regime

ABX represents the minimal desired following distance of vehicle n. This can be interpreted as the point where a driver notices he comes to close to his leader while car-following, or the point where the driver notices his method of approaching is not sufficient to avoid collision. It is defined as:

$$ABX(n, v) := \ AX \ + \ BX \qquad \text{Equation 5}$$

With

$$BX(n, v) := (BXadd + BXmult * RND1_n) * \sqrt{v} \qquad \text{Equation 6}$$

Where $BXadd$ forms a baseline and $BXmult$ and $RND1_n$ creates a vehicle dependent part. And v is defined as:

$$v := \{\begin{matrix} v_n & when & v_n \leq v_{n-1} \\ v_{n-1} & when & v_n > v_{n-1} \end{matrix} \qquad \text{Equation 7}$$

Note that both $AX(n)$ and $BX(n)$ are dependent on $RND1_n$ which means AX and BX are fully correlated. This seems logical as a high $RND1_n$ would describe a driver with a tendency to have a high following distance.

Also, line ABX should be a parabolic shape with an exact shape based on the actual speed of vehicle n, as long as $\Delta v < 0$. For $\Delta v > 0$ the exact shape is based on actual speed of vehicle $(n - 1)$, which if this vehicle has a constant speed would result into a horizontal line. Due to Image 2 being a more general image, it cannot be determined from the image if PTV[4] has changed the formulation. However, it is odd, that line ABX is not horizontal to the right of the d axes in Image 2. Therefore, a change of formulation could be possible.

3.1.1.3. SDV: the action point of the approaching regime

This threshold marks the point in time that a driver consciously realizes that he is closing in on another vehicle. It is defined as a relative velocity dependent on the distance headway. The exact definition is:

$$SDV(n, \Delta x) := \left(\frac{\Delta x - L_{n-1} - AX}{CX}\right)^2 \qquad \text{Equation 8}$$

With:

$$CX(n) := CXconst * (CXadd + CXmult(RND1_n + RND2_n)) \qquad \text{Equation 9}$$

Note that $CXmult$ is multiplied by both $RDN1_n$ and $RDN2_n$ this causes the perception distance and the preferred following distance to be partially correlated. Also note that Equation 8 can be rewritten in the form:

$$SDV := c_{1,n} * \Delta x^2 + c_{2,n}^2 \qquad \text{Equation 10}$$

In which c_i is the outcome of all the constants combined. Which means the line SDV for a certain vehicle is always a perfect parabola with its peak on the $(\Delta x = 0, \Delta v = c_n^2)$. In Image 2, however, the line SDV is quite obviously not a parabola. This causes concern on whether PTV has redefined the line SDV. This observation also shows that the figure that Olstam and Tapani [49] made in their paper "Comparison of Car-following models" that should represent the threshold in the Wiedemann model, is not accurate.

3.1.1.4. SDX: the action point of the free flow regime based on large headway

SDX is the action point that describes the moment a car-following driver consciously recognizes that he is leaving his leader. It is defined as a distance dependent on a speed difference, formulated as:

$$SDX(n, v, t) := AX + EX * BX \qquad \text{Equation 11}$$

With

$$EX(n, t) := EXadd + EXmult * (NRND_{n,t} - RND2_n) \qquad \text{Equation 12}$$

A new random variable is introduced in this function called $NRND_{n,t}$ which is not a driver dependent variable but one that changes over time. It is unclear if this variable is rolled 'once for each timestep' or 'once for each driver in each timestep'. In this research the latter is assumed.

Equation 11 can be rewritten in the form of:

$$SDX(n, v, t) := c_{1,n} + c_{2,n,t} * \sqrt{v} \qquad \text{Equation 13}$$

[4] PTV is the company that develops the software package VISSIM

For a certain vehicle this means again a parabolic shape at the left side of the d axis (Image 2), depended on its own velocity. And a parabolic shape depended on the velocity of the leader on the right side of the d axis. which exact location depends on the vehicle and the timestep. The line SDX as shown in Image 2 could be a parabola, although hard to see. Therefore, it is assumed that PTV did not change the formulation of SDX.

3.1.1.5. $OPDV$: the action point of the free flow regime based on lower velocity

This is the threshold where a driver consciously recognizes that he has lower speed than his leader, this typically occurs at very small car-following distance. It is defined as:

$$OPDV(n, v, t) := SDV * EX^2 * (-OPDVadd - OPDVmult * NRND) \quad \text{Equation 14}$$

$OPDV$, like most of the other function will also yield a parabola. This seems to be the case in Image 2. Therefore, it is assumed that PTV did not change the formulation of $OPDV$.

3.1.1.6. Free-flow Driving regime

Whenever a vehicle is driving in free flow it will try to gain its desired speed. The acceleration/ deceleration a vehicle will make is defined by:

$$a_{max} := a_{max}mult * (V_{max} - V * FaktorV) \quad \text{Equation 15}$$

With

$$FaktorV := \frac{V_{max}}{V_{des} + FaktorVmult * (V_{max} - V_{des})} \quad \text{Equation 16}$$

In which V_{max} is the vehicle's maximum speed, V_{des} the desired speed and V the actual speed. And $A_{max}mult$ and $FaktorVmult$ are calibration parameters.

3.1.1.7. Approaching regime

Whenever the SDV threshold is passed towards the approaching area. The acceleration is based on:

$$a_{app} = \frac{1}{2} * \frac{(\Delta v)^2}{ABX - (\Delta x - L_{n-1})} + a_{n-1} \quad \text{Equation 17}$$

In which a_{n-1} is the acceleration of the leader.

3.1.1.8. Car-Following regime

Whenever the threshold to follow is reached a vehicle's acceleration is based on a_{null}. Whenever it is via the threshold of SDV or ABX, $a_n = -a_{null}$. And whenever it is reached via the thresholds OPDV or SDX, $a_n = a_{null}$. In which:

$$a_{null} = ANULLmult * (RND4_n + NRND) \quad \text{Equation 18}$$

Note that in this function there is a driver specific random number, which is new. Meaning that there is no correlation between following behaviour and braking behaviour in this model. Apart from that $NRND$ is added to create the unconscious variation in following behaviour.

3.1.1.9. Braking regime

Whenever the following distance becomes smaller than ABX, the braking regime will start. During this regime the acceleration a_{brake} is described by:

$$a_{brake} = a_{null} + a_{min} * \frac{ABX - (\Delta x - L_{n-1})}{BX} \quad \text{Equation 19}$$

In which

$$a_{min} = -AMINadd - AMINmult * RND3_n + BMINmult * v_n \quad \text{Equation 20}$$

Note that, even though there is a threshold BX defined, reaching it does not cause the change of regime. The braking regime will stay active after passing this threshold, even when the vehicles would be overlapping / colliding.

3.1.2. Non-Wiedemann driver states

Apart from the driver states of the Wiedemann model, there are also different driver states. Among the known states are 'merge ending', yielding and synchronization. Merge ending occurs when a vehicle must do a necessary lane change, but it comes near the end of the merge area. In this case it will slow down and in case it reaches the end of the merge area, it will come to a standstill.

Yielding and synchronization are part of the advanced merging option in VISSIM this is further explained in 3.1.2.1. Sadly, the advanced merging option does not function well in case it is not combined with 'merge ending' this can cause some very inhuman interaction between two vehicles, this is presented in 3.1.2.2.

3.1.2.1. Advanced merging

In VISSIM two options can be selected that will make vehicles facilitate others that have to make a necessary lane change. These actions can be activated by the options ***advanced merging*** and ***Cooperative lane change***. ***Cooperative lane change*** is presented in paragraph 3.2. And ***advanced merging*** is presented here. ***Advanced merging*** adds two driver states to the model. In this research they are named synchronization and yielding.

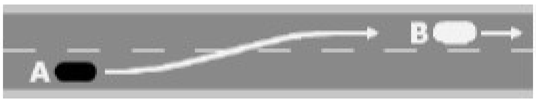


Image 3 Synchronization (copy from VISSIM 8 manual) [44]*

Synchronization is explained based on Image 3. Whenever a vehicle (A) must make a necessary lane change, and it sees a vehicle (B) downstream in the target lane. If vehicle B is about equal speed of vehicle A (-1 m/s $< \Delta v <$ 1 m/s), then vehicle A will slow down to fit in the gap with $a = -0.5$. [44]*

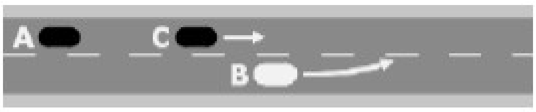


Image 4 Yielding (copy from VISSIM 8 manual)[44]*

Yielding is explained based on Image 4. It can occur when a vehicle (C) notices another vehicle (B) on a different lane downstream which must make a necessary lane change into the lane of vehicle C. In this case, vehicle C will do cooperative braking. The exact formulation of a remains unknown to the public.

Note that Vehicle A in Image 4 will also yield for vehicle B. This means that the followers in an ATP of vehicles can also trigger the yield regime. However, in the manual it is not specifically stated for how many vehicles down the line the yield regime can be activated.

3.1.2.2. The deadlock of advanced merging

In most situations advanced merging will make the merging location closer towards the location where the vehicle encounters his need to make a necessary lane change. However, in rare situations combining yielding and synchronization will cause a semi deadlock. This lock will not persist infinitely but can persist for over 2 km or until the vehicle reaches the end of the merging section. The cause of the deadlock is uncertain, due to the lack of exact formulation of yielding and synchronization. However, a possible reason is presented here.

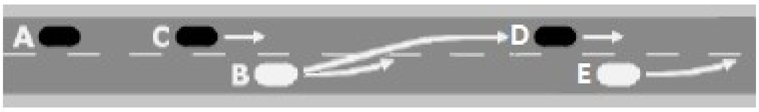


Image 5 Deadlock of advanced merging

The deadlock is explained based on Image 5. If $v_D > v_E$ then vehicle D will brake to yield for E. Vehicle B will brake to synchronize with D with a deceleration of a_B and vehicle C will brake to yield for B with a_C. In the simulations it can be observed that a_B and a_C are extremely close but a_B is smaller. This causes vehicle B to end up next to vehicle C and thus unable to merge. The deadlock is solved over time if Δx between C and D get sufficiently large so that vehicle B stops synchronizing with D, or whenever vehicle C overtake vehicle B, in which case vehicle B will synchronize with C. If the latter happens, however, there is a risk that Δv of vehicle B and A become so large, that vehicle A will change his state and stops yielding for B. As mentioned earlier this lock can persist for over 2 km. One of the methods to solve the deadlock is a cooperative lane change, which is further described in 3.2 *Lateral behaviour.*

3.2. Lateral behaviour

The exact lane change models that are implemented in VISSIM are unknown, although it is known that VISSIM is created out of a base of MISSION. In this paragraph the lateral behaviour of the MISSION model is described. It is assumed here that the VISSIM model does not have large deviations from this.

According to Wiedemann and Reiter [31], the lane change model of MISSION was based on the research and measurements of Willman [50] and Sparmann [45]. Due to the authors inability to read German, the insights of those books will only be presented via the interpretation of "Wiedemann and Reiter" and "Fellendorf and Vortisch" [43].

Like the Gipps model the lateral model of VISSIM is also based on a decision tree like system. Fellendorf and Vortisch give a quite detailed description of the layout of it, but do not mention their source.

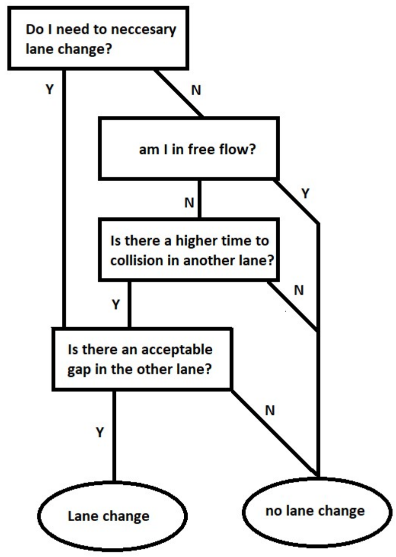


Image 6 Basic lateral behaviour decision tree (Based on writing from Fellendorf and Vortisch) [43]

As can be seen in Image 6, the first check is on a necessary lane change. VISSIM distinguishes between a necessary lane change and a normal lane change. A necessary lane change occurs whenever a vehicle n needs to change lane to follow its route. Vehicle n will notice it has a necessary lane change based on network setting of the specific link connecter that is next on the route for vehicle n. If a necessary lane change is present, then a gap check will happen towards the target lane.

If answered with 'No', the second check is on free flow state, this refers to the free flow of the Wiedemann model as described in 3.1.1. In case a vehicle is in a free flow state, according to Fellendorf and Vortisch no lane change will happen. However, this is not entirely true, because if the setting ***right-side rule*** is turned on, then a vehicle, even in free flow state, will change lanes until it reaches the far-right lane.

If a vehicle is not in free flow state, there is a check on time to collision. Whenever time to collision is lower in another lane, that lane is selected as the target lane. In case of a ***right-side rule***, the target lane is always to the left. However, in case of ***free lane selection***, the method of selecting a target lane is not described.

Whenever a target lane exists, the gap acceptance model becomes active. The exact formulation of this piece of the algorithm remains unknown, but its complexity is described in Wiedemann and Reiter [31]. Wiedemann and Reiter describe how the gap acceptance model distinguishes first between lane change to a 'faster lane' or 'slower lane'. For a lane change to a faster lane, four different algorithms can be used depending on how the lane change is categorized. For a lane change to a slower lane there are two different algorithms. The different functions of the algorithms are named, but no formulation is given.

Apart from that, Fellendorf and Reiter mention that for necessary lane changes, the gap acceptance model is based on the distance towards the emergency stop[5]. Meaning that if the urgency to lane change increases, the gap acceptance model accepts smaller gaps. However, there is no parameter to calibrate the urgency effect in VISSIM.

Apart from the standard lane changing, there is also an extra tactic added to the simulation called ***Cooperative lane changing***. This tactic involves a lane change of vehicle n in order to make space for another vehicle m that has to make a necessary lane change into the lane of vehicle n. The exact formulation of a cooperative lane change is unknown. The calibration variables, however, are maximum speed difference (Δv_{max}) and maximum collision time ($t_{c,max}$). This suggests that vehicle n will select a target lane in case:

$$v_n - \Delta v_{max} < v_m < v_n + \Delta v_{max} \qquad \text{Equation 21}$$

And

$$\frac{d_n}{v_n - v_{n-1}} < t_{c,max} \qquad \text{Equation 22}$$

Unfortunately, this remains unconfirmed. It is assumed that the method of gap acceptance is equal to that of a normal lane change.

3.3. Method of assigning behaviour

In VISSIM the driving behaviour is defined in a ***Driving behaviour*** object. The method to bring the driving behaviour to a certain vehicle is a multistep process, with different objects related to it. A ***Link*** has a ***Link behaviour type*** that contains a ***Driving behaviour*** for a certain ***Vehicle Class***. In a ***Vehicle class*** multiple ***vehicle types*** can be referred to under the same name. In Table 4 the different objects are described in more detail.

[5] The emergency stop is a location where a vehicle will come to standstill if it did not manage the necessary lane change

Table 4 Objects related to behaviour assignment

Object class	function	contains
Vehicle type	Defines vehicles of the same type, can a very specific vehicle with set values that describe it (e.g. a Truck of EcoTwin). Or a vehicle set/group which has characteristics based on distributions (e.g. a passenger car in general).	• Dist. on vehicle length • Dist. on acceleration • Dist. on deceleration • (external driver model)
Vehicle Class	Grouping different vehicle types. Used by other objects when referring to rule changes for vehicles.	• List of ***vehicle types***
Driving Behaviour	Defines calibration parameter for the driving model inside an object	• All driving behaviour calibration parameters
Link behaviour types	Define the type of road that a certain link is. It links driving behaviour object to vehicle classes	• Link between ***Driving behaviour*** and ***Vehicle classes***
Link	Defining a link in the network. This contains both the spatial aspects (length, lanes,etc.) as well as what type of behaviour is expected	• Location start • Location end • Lanes • Special lane rules • **One** behaviour link type

Note that a link can contain multiple lanes, but it cannot contain more than one ***Link behaviour type***. This means that if a link contains two lanes main carriageway and one lane on-ramp. The behaviour of the on-ramp is always equal to the behaviour of the main lanes, which is often not the case when examining empirical data, e.g. the speed on an on-ramp is lower [51], [52]**. To change behaviour on different lanes the COM server could be used to change the vehicle types based on the lane a vehicle is on. However, this is quite a time intensive procedure.

A second method of assigning behaviour is via an external driver model. In this case the driving behaviour is directly linked to the vehicle class. This means that the link is not included when assigning behaviour to a certain vehicle and therefore behaviour from the driver model is link independent. If one would like a link dependent behaviour, one has to hard code this within the driver model. This method is used in this research to describe the ATPs, more on this in chapter 4.

3.4. Validation the default settings in VISSIM

The data for the acceleration from a standstill have been validated against the test vehicle data gathered in the 2004 European research project RoTraNoMo [44]*. Sadly, the actual method of how the data are gathered and processed remains unknown. No papers on RotTraNoMo where found, and the website does not exist anymore.

On the calibration of all the other parameters, Menneni, Sun and Vortisch did a calibration on the USA motorway 101 (United States of America). They concluded that the speed-flow diagrams of VISSIM did match those of the real-life data. Sadly, their paper is not available for TU Delft or TNO. Therefore, no further conclusions can be drawn on the quality of the validation, or the applicability to European roads.

3.5. Discussing VISSIM

In the discussion of VISSIM the three topics are discussed: the longitudinal model, the lateral model and the interaction of ATP and conventional vehicles.

On the longitudinal model, the longitudinal model in VISSIM is more than 30 years old, it has had no large adjustments in all those years. Given the advancement of the computational calculation speed, one could argue that the model lacks detail, and more features could be added. Apart from that, in the VISSIM manual it is only stated that the longitudinal model is based on the Wiedemann model. PTV does not formulate which changes have been made. However, the model has been used in a wide variety of simulation studies and, as can be read in chapter 4, have also been used to model ATPs before.

About the lateral model, PTV has done a lateral model overhaul in the past ten years and added the feature of cooperative lane changing and advanced merging. Given the naming of the systems and its explanation, it seems that the model update included some of the features first presented by Wang *et al.*[53] in 2005. However, the lack of clarification and referencing suggest otherwise. The uncertainty on the formulation of these algorithms make scientific analyses using VISSIM difficult. Because it is impossible to check the trade-offs made during the development and weaknesses remain well hidden.

On the interaction of ATP and conventional vehicles, as mentioned in paragraph 2.3, it is expected that vehicles will merge into smaller gaps and will have a lower velocity on the acceleration lane. Lowering the velocity is possible in VISSIM. However, lowering the critical gap of conventional vehicles when interaction with ATP is not possible unless the critical gap is also lowered when conventional vehicles interact with other conventional vehicles. Therefore, it chosen not to make any changes to the critical gap size.

4. Automated truck platoon control model

In this chapter first the different approaches to describe ATP behaviour are reviewed. Then a selection is made to create an ATPCM, in which, in case no earlier algorithms were found, a new design is presented. In the last paragraph the implementation of this ATPCM into VISSIM is described.

4.1. Theory on Automated truck platoon control model research

For platooning vehicles, only studies into longitudinal control have been found. Of these studies there are two groups, (1) the review and designs of longitudinal control algorithms and (2) simulation studies of platooning vehicles. In this paragraph both groups are reviewed in their separate sub paragraphs. Of the simulation studies only the method to model ATPs and conventional vehicles is reviewed.

4.1.1. Longitudinal control algorithms

In an ATP, vehicles have different roles. The leader is a manually driven vehicle, while all other vehicles are followers. The manually driven leader can be represented by a driver model and therefore will not be described in this paragraph. The following vehicles however should use a car-following algorithm that takes over the longitudinal control. In this paragraph different approaches to the longitudinal control are presented.

In the last decades, car manufacturers have implemented automated vehicle guidance systems that assist or take over longitudinal control into their vehicles. The exact formulation of such systems is often unknown due to manufacturers trying to protect their intellectual property. Nevertheless, scientists have made proposals for such systems and published their ideas.

Apart from self-driving cars there are also driving assisting systems that take over part of the driver's tasks. For longitudinal behaviour on the motorway, such systems are adaptive cruise control (ACC) and connected ACC (CACC).

Taking algorithms for longitudinal behaviour from an already self-driving vehicle is impossible. Therefore, the next best option is to take algorithms of driver assistance systems that take over longitudinal tasks.

In 1993, Ioannou and Chien [54] proposed the first adaptive cruise control algorithms. This control law was still likely to create oscillation in distance headway between vehicles when they are in string of vehicles and all are equipped with this system. Next to this problem, it also had a risk of collision if the first vehicle would do abrupt, heavy braking. To solve this issue collision avoidance systems have been developed, those are addressed at the end of this paragraph.

The measurement of the velocity of a vehicle is calculated by measuring the headway distance of a vehicle twice. This results in a velocity difference between the two vehicles and that can be used to calculate the velocity of the leader. This means that two measurements must be made to calculate the velocity of the predecessor and this causes a delay in information. During a braking action of the first vehicle, this delay in information will cause the vehicles in a string to brake heavier for each vehicle down the string.

The difference in deceleration causes oscillation in headway distance and gets worse further down the string. To solve the problem with oscillations a connected ACC (CACC) has been presented by multiple researchers [55][56], the communication system should communicate the severity of the braking action and the velocity of the vehicle. This will reduce the information delay to the WIFI speed and create an option to also contain information about the vehicle in front of the leader

A Design for a CACC algorithm specially for trucks has been presented by Ploeg *et al.*[57][58]. Due to the applicability of this CACC design in this research, Ploeg *et al.*'s formulation is presented in more detail. Their design is based on an attempt to create a constant time headway policy for a desired distance (d_r). Which applies only to followers in an ATP. It is formulated as:

$$d_{r,n}(t) = r_n + h_n\, v_n(t) \qquad \text{Equation 23}$$

In which r_n is the stand still distance and h_n is the time headway. In this research only a homogenous string is assumed therefore $h_n = h$, because it is independent of vehicle ID. Ploeg formulated the spacing error $e_n(t)$ as:

$$e_n(t) = d_n(t) - d_{r,n}(t) \qquad \text{Equation 24}$$

In which d_n is defined as the distance between the front of the leader $(n-1)$ to the front of the follower n. As a basis of control design the following model is adopted:

$$\begin{pmatrix} \dot{d}_n \\ \dot{v}_n \\ \dot{a}_n \end{pmatrix} = \begin{pmatrix} v_{n-1} - v_n \\ a_n \\ -\frac{1}{\tau}\, a_n + \frac{1}{\tau}\, u_n \end{pmatrix} \qquad \text{Equation 25}$$

In which τ is a time constant representing the engine dynamics and u_n is the preferred acceleration. The control law is designed as:

$$\begin{pmatrix} e_{1,n} \\ e_{2,n} \\ e_{3,n} \end{pmatrix} = \begin{pmatrix} e_n \\ \dot{e}_n \\ \ddot{e}_n \end{pmatrix} \qquad \text{Equation 26}$$

The third state equation can be formed by differentiating $e_{3,n}$ and using Equation 23 and Equation 24 which results in:

$$\dot{e}_{3,n} = -\frac{1}{\tau}\, e_{3,n} - \frac{1}{\tau} q_n + \frac{1}{\tau}\, u_{n-1} \qquad \text{Equation 27}$$

In which u_{n-1} is the desired speed of the predecessor, therefore communication between vehicles is necessary. q_n is the new input which is defined as:

$$q_n := h\, \dot{u}_n + u_n \qquad \text{Equation 28}$$

The function of q_n is to stabilize the error term while adjusting for the input of the leader. Solving the equation $\lim_{t \to \infty} |e_n(t)| = 0$ the control law results in:

$$q_n := K \begin{pmatrix} e_{1,n} \\ e_{2,n} \\ e_{3,n} \end{pmatrix} + u_{n-1} \qquad \text{Equation 29}$$

With K being the calibration parameter set containing $(k_p \; k_d \; k_{dd})$. The final control model yields:

$$\begin{pmatrix} \dot{e}_{1,n} \\ \dot{e}_{2,n} \\ \dot{e}_{3,n} \\ \dot{u}_n \end{pmatrix} = \left(\begin{array}{ccc|c} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\frac{k_p}{\tau} & -\frac{k_d}{\tau} & -\frac{1+k_{dd}}{\tau} & 0 \\ \frac{k_p}{h} & \frac{k_d}{h} & \frac{k_{dd}}{h} & -\frac{1}{h} \end{array} \right) \begin{pmatrix} e_{1,n} \\ e_{2,n} \\ e_{3,n} \\ u_n \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{h} \end{pmatrix} u_{n-1} \qquad \text{Equation 30}$$

Note to create a stable string K should be chosen considering: $k_p, k_d > 0$, $k_{dd} > -1$ and $(1 + k_{dd})k_d > k_p\tau$. If these criteria are met, the string is stable for a homogeneous string of vehicles.

CACC is a system created for comfortable car-following and not as a collision avoidance system. Xiao et al. [59] remarks that CACC designs such as those of Ploeg do not guarantee collision safety.

In case the CACC of Ploeg is used as car-following method as an ATPCM then a collision avoidance system should be implemented separately. Collision avoidance systems are already widely used. However, the exact formulation of the control algorithms remains intellectual property of the car manufacturers. Therefore, no formulation can be presented of a collision avoidance system that is currently on the road. However some collision avoidance have been proposed such as the safe distance controller for ACC systems by Broqua *et al.* [60]. Broqua's design was very similar to Gipps' car-following model.

4.1.2. Simulation methodologies

In this paragraph only simulation studies are included that contain an interaction between conventional driving models and ATPs, in which the conventional vehicles are modelled with a different driver model from the ATPCM. The author has found four studies in this category.

Müller [13] used the VISSIM software package to model an interaction between VISSIM and CACC on a straight three lane carriageway. The conventional vehicles are modelled using the Wiedemann driver model, as mentioned in chapter 3 the default is in VISSIM. The CACC is modelled by Müller by creating a vehicle that is as long as an ATP would be. This brings a whole set of limitations including: the ATP unable to break, no cut-ins are possible, the interaction between the leader and the follower cannot be observed and string instability cannot be observed. To model interaction of ATP with conventional vehicles this method does not suffice because this model does not model an ATP following control model, just an estimation of what CACC would do to a length of an ATP.

Deng [14] also used the VISSIM software package to model interaction between VISSIM and CACC. Deng simulated a two-lane straight carriageway including an off-ramp. Deng spawns ATPs of three vehicles directly by using the COM-server of VISSIM. When the ATP reaches the off-ramp, it will increase its headway and when it has passed the off-ramp it will decrease it again. Deng 's method would suffice to answer the research questions, although, as mentioned in the problem description, decoupling at every ramp would not be a workable solution in the Dutch road network. Deng does not include a collision avoidance system.

Ramezani [5] used an adjusted Gipps model to simulate conventional vehicles that interact with ATPs that use ACC and CACC. As collision avoidance system Ramezani lets the Gipps model take over control whenever it suggests an acceleration lower than 1,6 m/s^2. Ramezani intended to model a human driver taking over control whenever the driver would feel heavy breaking was needed. This was also possible because the time headway between the trucks in the ATP was 0,9 s in Ramazani's models.

Van Maarseveen [15]** used an IDM+ and LMRS model to simulate conventional vehicles that interact with ATPs equipped with CACC. As a collision avoidance system Van Maarseveen used an R function to increase the response on the velocity error in the CACC at small headways. The idea of an R function was first proposed by Mullakkal-Babu *et al.* [16] and is formulated as:

$$R = \frac{-1}{1 + Q\,e^{-\frac{d_n}{P}}} + 1 \qquad \text{Equation 31}$$

In which Q and P are calibration parameters and d_n is the distance headway. Van Maarseveen used this combination of models to simulate ATPs with headways between 0,3 s to 1,2 s.

4.1.3. Conclusion on suitable algorithms

All found ATP simulations that model interaction with conventional vehicles use a CACC algorithm as car-following method. The difference lies in the implementation of the collision avoidance and the detail in which the separate vehicles of an ATP are modelled.

4.2. Algorithm selection and design for the ATP control model

Based on the findings in paragraph 4.1, in this paragraph a selection of longitudinal algorithms is done to create an ATPCM which has string stable behaviour and does not collide during the simulations. Where needed, proposals are made to make sure the ATPCM is functional during all situations encountered in the simulation model network. The simulation model network is further described in chapter 5. The implementation of the selected algorithms in VISSIM are described in paragraph 4.3.

4.2.1. Longitudinal control algorithms

The control model used for the leader must be different from the control model of the followers, because the leader represents a human driver and the followers use CACC. To mimic the human driver, it is chosen to use the Wiedemann driver model implemented in VISSIM.

The follower are modelled using a CACC algorithm, however, the CACC as proposed by Ploeg *et al.* [57] requires the desired acceleration of the vehicle in front. In real vehicles this can be measured by measuring how far the gas pedal is pushed in, however in the Wiedemann model such a parameter does not exist. Ploeg, however, did propose another CACC algorithm which has two error terms instead of three [61]*. This model uses the desired velocity of the vehicle in front instead of its desired acceleration. In a simulation environment the desired velocity can be easily calculated. This CACC design is intellectual property of TNO and therefore is described in the confidential Appendix 1. The proposed values of the calibration parameters are also present in Appendix 1.

This two-error-term CACC design does not guaranty collision safety. However, the idea of Broqua [60] to use part of a driver model as a collision avoidance system, triggered idea to use Wiedemann as collision avoidance system. The ATPCM is designed in such a way that the followers will use CACC in following situations and use the Wiedemann model to do heavy braking. The braking regime will start whenever the Wiedemann model suggests a braking action with lower acceleration than -2,5 m/s^2.

Apart from the behaviour of an ATP, creating an ATP in the first place is a challenge as well. In paragraph 5.2.1.2 the method to create a platoon inside the model is described, the method used to create platoons will not influence any results as long as the method guaranties that 100% of all the ATP vehicles are within a platoon of three vehicles.

4.2.2. Lateral control algorithms

To be able to estimate how much distance ATPs require to change lanes, the simulations will require ATPs to be able to change lanes. To describe lane changing of an ATP, three distinct categories must be addressed: (1) the lane change decisions for an ATP as a whole, (2) lane change decision for a single vehicle and (3) the lateral movement. Each is addressed in this paragraph.

On the lane change decisions as for an ATP as a whole, to the authors knowledge, no automated system for lane changes has been designed and published. In this research a proposal for the lane change logic of an ATP is presented. The proposal is based on the idea of mimicking the behaviour of small military convoys. The goal of a military convoy is to stay together while changing. This is accomplished by having no cut-ins and the vehicles do not overtake each other. A military convoy accomplishes this by letting the rear vehicle (n) make the lane change first. Vehicle n will reduce its speed after the lane change, this creates a gap in front for vehicle $(n-1)$ which will disconnect from the convoy in the old lane and connect to the rear vehicle as new front. The vehicles in the new lane keep their reduced speed until all vehicles in the convoy have made it into the new lane.

The idea of the convoy is adopted but slightly changed. Instead of letting the vehicles change lane one by one, the rear vehicle goes first and then the rest follows. This is done because it allows all vehicles, that are not rear or front, to be fully automatic and in no need for a driver. In Image 7 the lane change tactic is visualized using four phases that occur chronologically, the white vehicles represent an ATP and the black vehicles represent other traffic.

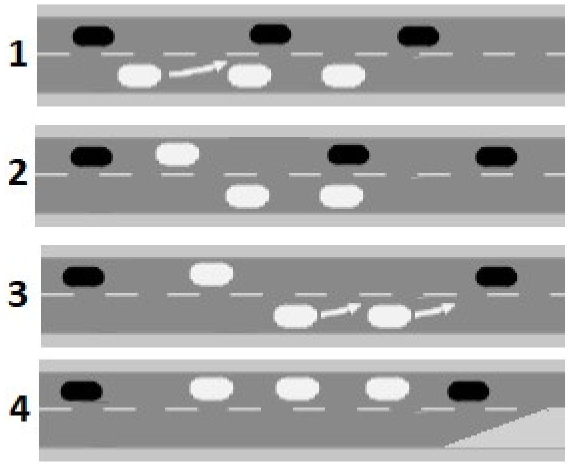


Image 7 Four phases in ATP lane changing

About the lane change decisions for a single vehicle, the behaviour of the rear vehicle (n) is the same as the Wiedemann model in VISSIM, this simulates the effect of the vehicle decoupling from the ATP and making a lane change into a gap that would also be accepted by a human driver.

The lane change decision of the leader is based on the headway of vehicle (n), whenever $d_n > platoon\_length$ the leader will make a lane change. The lateral behaviour of the middle vehicle of the ATP is the same as the behaviour of the leader. Which means it will also make a lane change if the leader does so.

The exact lateral movement of each vehicle is adopted from the default in VISSIM. This includes all the lateral behaviour except for the decision whether to make a lane change or not.

4.3. Implementation into a VISSIM model

To implement all the demands that are presented earlier in this chapter, a design is proposed that contains behaviour for different ATP roles. Each role will have different lateral and / or longitudinal models. An overview of the roles and models is given in table 5. To clarify the context at which the roles occur, some typical situations with identified roles are shown in Image 8.

Table 5 Overview of sub-models in the TP driver model

Role	Longitudinal models	Lateral models	Shown in Image 8 as vehicle:
Unconnected	• Wiedemann ($v_{d,n}$)	• VISSIM Lateral	A
Connecting	• Wiedemann (connecting v_d)	• VISSIM lateral	B
Leader	• Wiedemann (minimal v_d)	• ATP lateral[6]	C
Middle	• CACC • Wiedemann (collision avoidance)	• ATP lateral	D
Rear of 3	• CACC • Wiedemann (collision avoidance)	• ATP lateral	E
Rear of 2	• CACC • Wiedemann (collision avoidance)	• No lane changing	F

In this paragraph firstly, the logic on role determination is explained. Than the logic behind selecting longitudinal models is explained followed by the exact implementation of the models. Lastly the implementation of the lateral models is explained.

Note that the simulated physical aspects of every vehicle are identical, meaning that the ATP vehicles are all homogeneous. To create homogeneous vehicles in VISSIM one must remove the variance of the maximum acceleration, maximum deceleration, engine power and weight of the vehicle. How this is done is explained in Appendix 3.

4.3.1. Role Determination

Whenever ATP vehicle n is spawned it will always be in ***Unconnected*** state by default. Each timestep the list of roles is checked until a role is found. This is done in a distinct order, and when one is selected the procedure stops. A role is

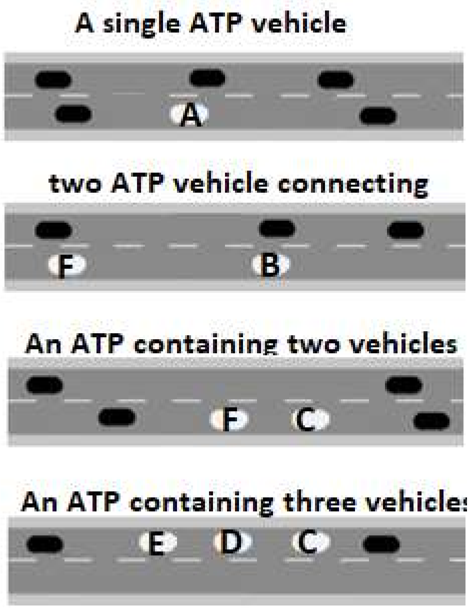


Image 8 ATP vehicle roles in different circumstances

[6] This model is first proposed in this research

selected if all the conditions for that role are met. The order, roles and conditions are shown in Table 6. For clarity an example of how the role selection goes is given.

Vehicle n is spawned as ***Unconnected***, at some point vehicle $n-1$ is an ATP and within range to connect (the maximum range is set to 200 meters). Vehicle n will turn to state ***Connecting***, which will result in the two vehicles coming close together. At some point vehicle $n-1$ will have a headway small enough to start the CACC and will gain the state ***Rear of 2***, the CACC range is set to 75 meters. Eventually the headway will reduce to under 50 meters which is set to be the connecting minimum, at this point vehicle n will gain state ***Leader***, this will make vehicle n move to a velocity that is the desired velocity of the ATP. AN ATP of two vehicles is now created. If behind this platoon another ATP vehicle $n-2$ would appear, the same sequence will happen. First vehicle $n-1$ will connect to it, if the gap between vehicle n and $n-1$ will become larger than the minimal connect distance, vehicle n will start connecting again too. This will cause all gaps to close and eventually an ATP of three is created.

To speed this process up a ramp meter is implemented in the model, this ramp meter is a design of M. Salomons. The algorithm us described in Appendix 2.

Table 6 Role determination from the standpoint of vehicle n

Order	Role	Conditions
1	***Rear of 3***	• Vehicle $n+1$ is an ATP • Vehicle $n+1$ has state ***Middle*** • $d_n < d_{CACC}$
2	***Connecting***	• Vehicle $n-1$ is an ATP • $d_{connect,min} \leq d_{n-1} < d_{connect,max}$
3	***Leader***	• Vehicle $n-1$ is an ATP • $d_{n-1} < d_{connect,min}$ One of the following: • Vehicle $n+1$ is not an ATP • Vehicle $n+1$ has state ***Rear of 3***
4	***Middle***	• Vehicle $n-1$ is an ATP • Vehicle $n+1$ is an ATP • Vehicle $n+1$ does not have state ***Leader*** • $d_n < d_{CACC}$ One of the following • Vehicle $n-1$ has state ***Leader*** • Vehicle $n-1$ has state ***Connecting***

Order	Role	Conditions
5	***Rear of 2***	• Vehicle $n-1$ is an ATP • Vehicle $n-1$ has state ***Leader*** • $d_n < d_{CACC}$
6	***Unconnected***	• Default

4.3.2. Implementation of the multiple Wiedemann models

As mentioned above, all models are implemented in a single ATPCM. This does not mean that in every timestep all the models are calculated. What is calculated every timestep is one version of the Wiedemann model and next to that is in some cases the CACC running too. As can be seen in Table 5 however, there are four implementations of the Wiedemann model (normal, connecting, minimal and braking). All except the braking model consist of the default Wiedemann model that is active for longitudinal behaviour. The difference however is the desired velocity that is the input for the model.

Whenever an ATP vehicle is spawned it will gain a desired speed based on a random number that selects a desired speed from the desired speed distribution. The ATPCM will save this value in its memory and use this value as input for the Wiedemann model if the vehicle is ***Unconnected***. When a vehicle is in ***Connecting*** state, it will change the input desired speed for the Wiedemann model based on the vehicle behind it. It is formulated as:

$$v_{d,input} = v_{d,n+1} * C_{connect} \qquad \text{Equation 32}$$

In which $v_{d,n+1}$ is the followers' desired speed at spawn. And $C_{connect}$ is a reduction factor to close the gap. In the models this reduction factor is set to 0,9.

When a vehicle is the ***Leader*** of an ATP, it should behave as a human. But some other factors should be modelled too. For example, some trucks are loaded differently from others, which could result in a different maximum or desired speed. And to keep an ATP together it can only go as fast as its slowest member. To model this effect the ***Leader*** of an ATP will use the Wiedemann model with minimal desired speed in the ATP. Formulated as:

$$v_{d,input} = \begin{cases} \min(v_{d,n}, v_{d,n+1}, v_{d,n+2}) & for\ platoons\ of\ 3 \\ \min(v_{d,n}, v_{d,n+1}) & for\ platoons\ of\ 2 \end{cases} \qquad \text{Equation 33}$$

In which $v_{d,i}$ is the desired speed at spawn for vehicle i.

The last application of the Wiedemann model is as a collision avoidance model, this is explained at the end of sub-paragraph 4.3.3.

4.3.3. Connected Adaptive Cruise control and Collision Avoidance implementation

As mentioned above the vehicles in state ***Middle***, ***Rear of 2*** and ***Rear of 3*** are using a CACC model to mimic car-following behaviour. Although this model is based on the published work of Ploeg *et al.* [58]. The proposed model uses the desired acceleration of the predecessor u_{n-1}. This causes a problem in application into the VISSIM model due to the Wiedemann model not using a parameter that is like u_{n-1}. Which causes the differential equation to lack a boundary condition and therefore becomes unsolvable. Assuming $u_{n-1} = 0$ does not work. Although when an ATP is moving at its desired acceleration, $u_{n-1} = 0$, the situations where it is not 0 are always happening earlier. And the algorithm will not reach equilibrium if $u_{n-1} = 0$.

Also attempts have been made to estimate u_{n-1} based on current acceleration and past acceleration, this would calculate the u_{n-1} of the past timestep. However, the time delay will cause massive string instability and therefore this does not work.

To solve this Ploeg has designed a similar CACC controller which does not use desired acceleration as the metric for communication, but desired velocity [61]*. This model is Intellectual property of TNO and therefore is described in confidential Appendix 1. Like the CACC algorithm described 4.1.1, this model is a differential equation which must be solved analytically. If a numerical method (like Euler forward) is chosen to solve the differential equation, the string will become very unstable. This is because solution of a numerical method is equal to the first order Tayler expansion of the analytical solution and therefore lacks the appropriate accuracy [62]*.

As mentioned above, the CACC algorithm has collision risk, therefore a collision avoidance part is simulated by the Wiedemann model (with $v_{d,input} = v_{d,n}$). It becomes active whenever the deceleration according to the Wiedemann model is higher than 3 m/s^2. If this occurs, the Wiedemann model will overwrite the CACC. However, this would often overwrite the close car-following behaviour at high speeds, therefore an extra rule has been implemented that deactivates the anti-collision system whenever a certain speed is exceeded. This speed is set at65 km/h. The solution for collision avoidance that is presented in this research cannot be implemented in real life systems, because the solution does not create a stable ATP under a velocity of 65 km/h. Also, collision safety is not guaranteed, however with during 10 hours of testing, no head-tail collision of ATPs vehicles occurred.

To give a visual indication of the action point design, an action point $(d, \Delta v)$ diagram is presented. To make the diagram, the action point between CACC and collision avoidance should be defined. Equation 19, determines the braking value of the behaviour in the braking regime of Wiedemann. As the action point between CACC and CA is based on an outcome of that function it can be described by that function.

To do this first Equation 5 and Equation 6 are simplified to:

$$BX = C_{BX,n} * \sqrt{v} \quad \text{Equation 34}$$

$$ABX = AX + BX = C_{AX,n} + C_{BX,n} * \sqrt{v} \quad \text{Equation 35}$$

In which $C_{AX,n}$ is the vehicle specific constant AX in the Wiedemann model, and $C_{BX,n}$ the vehicle specific constant used in the determination of BX.

Inserting Equation 34 and Equation 35 into Equation 19 and substituting for Δx yields:

$$\Delta x = \left(C_{BX,n} - \frac{(a_{brake} - a_{null}) * C_{BX,n}}{a_{min}} \right) * \sqrt{v} + L_{n-1} + C_{AX,n} \qquad \text{Equation 36}$$

Equation 36 describes the action point line between CACC and AC. To give an indication of the action points, the diagram from the perspective ATP vehicle following another ATP vehicle that is going 50 km/h is given in Image 9.

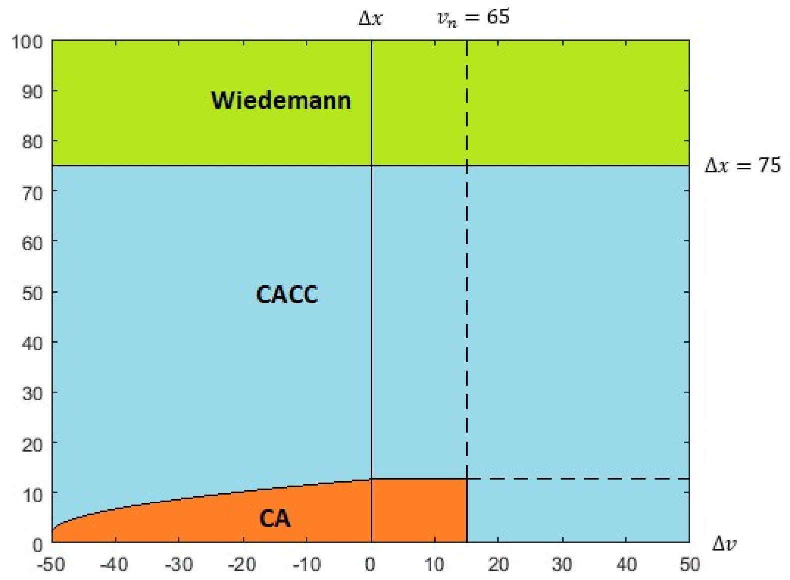


Image 9 Action point diagram of ATP followers

4.3.4. Implementation of the lane change algorithm

To make an ATP change lanes, the ATP as a whole must go into lane change mode, how this is done is explained in 4.3.4.1.The idea on how an ATP should change lanes is already explained in 4.2.2, the actual action points and logic behind it is explained in 4.3.4.2.

4.3.4.1. Recognition of a lane change

The ATPCM contains a flag-variable that describes if a vehicle is in an ATP that is doing a lane change. If this flag is non-zero, then the vehicle knows it is in lane change mode and it cannot change its role in an ATP anymore for as long as the lane change mode is on. This secures that during the lane change the ATP does not break up.

The lane change mode can be activated in two ways. The first method is: If the ***Leader***[7] is willing to make a lane change then it will turn its lane change mode on. The ***Rear of 3*** and ***Middle*** vehicles are only able to copy the lane change mode of the ***Leader***. This method can be used for carriageway split and keeping right after a carriageway merge.

However, for on-ramps this method is slow, because the lane change manoeuvre cannot be executed the moment that the ATP reaches lane change mode. For the second method a sign has been created that abuses the desired speed input of the ATPCM to pass other information. In VISSIM two speed signs have been created, one will tell

[7] ***Italic Bold*** words on in chapter 4 refer to specific roles of platoons as defined in the driver model

Leaders that a left lane change is coming and the other will tell ***Leader***s a right lane change is coming. These signs put the ATP into lane change mode.

4.3.4.2. Execution of a lane change

In this sub paragraph first, the lane change logic of the ***Rear of 3*** vehicle is explained, followed by the ***Leader*** and lastly the ***Middle***.

If an ATP reaches lane change mode all participants in the ATP will save the vehicle id of the ***Rear of 3*** vehicle and the vehicle id of the ***Leader***. The ***Rear of 3*** vehicle will fully disconnect from the ATP for the full duration of the lane change mode. This means that the longitudinal behaviour is a Wiedemann model, with a desired speed equal to the minimal member of the ATP $v_{d,min}$. This is the same desired speed as the ***Leader*** has as input for the Wiedemann model. The model will cause the ***Rear of 3*** vehicle to increase its headway. And it will use the Wiedemann lateral model to find a gap and make a lane change. ***Rear of 3*** will save that it made a lane change and cannot perform another one unless lane change mode has been turned off for at least one timestep.

During lane change mode the ***Leader*** will constantly check if his rear vehicle in the target lane is his saved ***Rear of 3*** vehicle. If this is the case it will check if ***Rear of 3*** has a headway long enough to fit the ATP in. In this research this value is set to 50 meters. When this is the case ***Leader*** will make a lane change into the target lane.

The ***Middle*** vehicle does the exact lateral movement of the ***Leader*** with a delay of one timestep. This lateral movement is defined as offset from the middle of the lane, therefore it will still function even in curves. This is easy to do in a model but not easily implemented in real life systems.

5. Simulation network design

When creating a simulation, apart from the driver models used, there is a wide range of parameters that have large impact on the outcome. Many of these parameters relate either to the physical layout of the modelled section or the demand from various types of vehicles on a section. In this chapter an attempt is done to find the best parameter settings which are required to answer the research questions.

To do so, in paragraph 5.1 the tactics which ATPs require in all the different types of road sections are identified and presented. To isolate challenges that relate to the research questions. In 5.2 road section types are chosen in which the main challenges occur in an isolated form.

When creating a simulation with the goal to contain a broad view on the situations that occur in the Netherlands, it seems logical to make multiple simulations and vary on the different parameters. However, this would cause immense simulation times, which would not be realistic to perform. Therefore, the choice has been made to simulate scenarios which are based on real world sections. The goal of this method is to gain insight in the sections which are at high risk of having problems with ATPs. This has the added benefit of the availability of origin-destination (OD) data that is available for such sections.

The selection of the real-world sections is done in 5.2. Being at high risk of having problems with ATPs is interpreted in this research as: A section with high truck share, on the main corridor between Port of Rotterdam and either Germany or Belgium.

5.1. Tactics the Dutch motorways require of ATPs

To deduce the tactics required of ATPs, the road sections on the Dutch highway that contain a possibility for mandatory lane changes are inspected. For each road section the possible conflicts are determined. For each of these conflicts the required tactic for an ATP is identified. At the end of the paragraph the tactics are listed.

The roadway section that are considered are: On-ramp, off-ramp, lane addition, lane reduction, joining carriageways, splitting carriageways, weaving area. In the images the red line is the path of the **ATP** and the green line is the path of **a conflicting vehicle**. A conflicting path is only described if there the vehicle has no other way to resume its path other than conflicting with ATP.

5.1.1. On-ramp

When the ATP encounters an on-ramp there are two possible scenarios. Either the ATP is on the main stream or the ATP is on the acceleration lane. In the first case the ATP will block the traffic on the acceleration lane from merging into the main stream. An illustration of this is given in Image 10 (left). Since all vehicles on the acceleration lane eventually need to merge into the main stream, the tactic for the ATP is to 'facilitate a predictable lane change'.

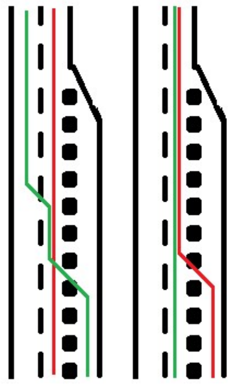


Image 10 Conflicts on an on ramp

In the other case the ATP on the acceleration lane needs to merge into the main stream. An illustration of this is given in Image 10 (right). The tactic on the ATP is to find a gap for lane change and then make the lane change. Since this type of lane change has a conflict zone, this tactic is referred to as a 'conflicted lane change'.

5.1.2. Off-ramp

When an ATP encounters an off-ramp, there are two possible paths the ATP can take. Either the ATP takes the off-ramp, or it keeps its course. Both paths are illustrated in Image 11.

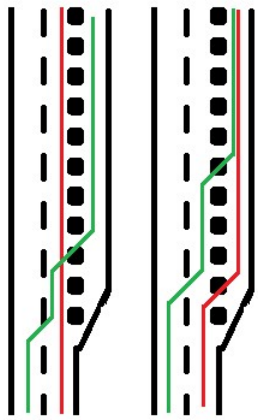


Image 11 Conflicts on off ramps

In the left part of the image the ATP must deal with a vehicle that has to pass the ATP to keep its path. Because not all vehicles on the left lane must take the off-ramp this merge can be unpredictable. Therefore, the ATP must be able to 'facilitate an unpredictable lane change.'

On the right side the ATP also must 'facilitate an unpredictable lane change.'. On top of that in this scenario the ATP also must make a lane change. Because there is no other traffic on this lane, there is no conflict. This tactic is referred to as a 'simple lane change'.

5.1.3. Lane addition and reduction

When a lane addition occurs, the ATP has to change lanes to keep the right lane of the carriageway, this is a 'simple lane change', equal to the manoeuvre of an off-ramp, this is illustrated on the left side of Image 12.

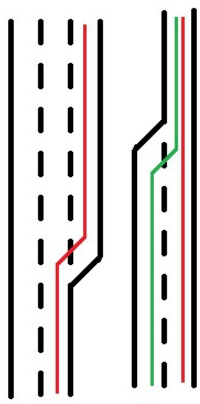


Image 12 Lane addition and reduction

On the right a lane reduction is illustrated. In this situation the ATP must be able to 'facilitate a predictable lane change' to create space for the merging traffic.

5.1.4. Joining Carriageways

When two carriageways join there are two possibilities. Either the ATP is on the right carriageway or on the left carriageway. In case the ATP is on the right carriageway no tactics are placed upon the ATP. If the ATP is on the left carriageway however a conflict does occur. This is illustrated in Image 13. Since the ATP should keep to the far-right lane and finds itself in the third lane. The ATP should change lane to reach the first lane. To do so, the ATP will need to make multiple 'conflicted lane changes' like taking an on-ramp, but in a different direction and without a limit to the distance it can take to finish the manoeuvre.

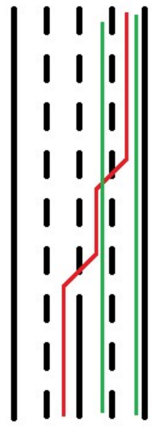


Image 13 Conflicts at joining carriageways

5.1.5. Splitting carriageways

When an ATP reaches a point where one carriageway splits into two, there are two possible scenarios, these are illustrated in Image 14. Either the ATP has a path on the right carriageway (left) Or the ATP has a path on the left carriageway (right). In case the ATP keeps right, there is no direct conflict with other streams, there is a risk however of a cut in, like the case of a lane reduction.

In case the ATP must go left, one or more lane changes to the left are needed. In the lanes the ATP merges, traffic is already present therefore this is a 'conflicting lane change' to the left. Apart from that it is also possible that that vehicles in the stream in the third or fourth lane, need to take the right carriageway. This results in a 'weaving conflict', This is different from a conflicted lane change since in weaving the lane changing vehicles could create gaps for each other.

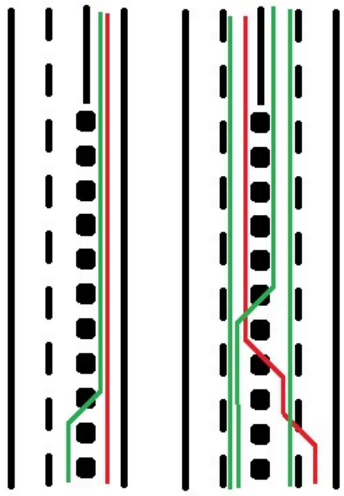


Image 14 Conflicts due to splitting carriageways

5.1.6. Weaving area

A weaving area is a combination of joining carriageways followed by splitting carriageways. Therefore, the conflicts that can occur in a weaving area are very similar to the ones in joining and splitting carriageways. There is one exception that has not been mentioned yet. In case an ATP enters the weaving area on the left lane, keeps its lane, and leaves left again conflicts occur, this is illustrated in Image 15 . In this conflict, vehicles that need to change carriageway must pass the ATP. The ATP will have to 'facilitate unpredictable lane changes' from both sides at once.

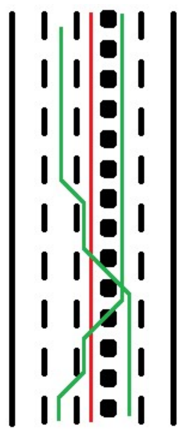


Image 15 Conflicts in a weaving area

5.1.7. Resulting tactics

Most of the demand that the road put on the ATPs should also be completed within a certain time frame or distance. This is the list of demands:

- Facilitate a predictable lane change from the right and left
- Facilitate an unpredictable lane change from the right and left
- Make a simple lane change to the right
- Make a conflicted lane change to the right and to the left.
- Make weaving manoeuvre to the right and to the left

5.2. 'Tactic isolation' and 'selection of road sections'

In this paragraph a selection is made on road sections which are the basis of the simulation scenarios. This goes as follows, firstly the tactics are compared and selected. Then a road section type s is chosen in which a selected tactic is relatively isolated from any other tactics. Lastly a real-world road section of type s is selected from truck corridors Rotterdam – Belgium, Rotterdam – Germany.

5.1.1. Tactic selection, facilitating lane changes

The behaviour of surrounding vehicles when confronted with a vehicle making a strategical (mandatory) lane change is different from the behaviour when confronted with a discretionary lane change. In real life the surrounding vehicles will guess, based on the road section and behaviour of the vehicle n, if a vehicle n is trying to make a mandatory lane change, or a discretionary one.

In simulation this is different, all vehicles know which vehicles are making necessary lane changes and will adjust their behaviour accordingly. This means that unpredictable lane changes, such as present near weaving areas and off-ramps do not exist in simulation. However, there is a distinct difference between facilitating vehicles from your lane to another and from another towards your lane. Therefore, two sections should be selected, one for vehicles with ATPs in their origin lane and one for ATPs in their target lane.

5.1.2. Road section selection, facilitating lane changes

To research the lane changes, both an on-ramp and an off-ramp are chosen. The choice to select on-ramps and off-ramps is because these sections create a very isolated environment for a unidirectional lane changing.

The off-ramp will simulate the interaction that appears when vehicles lane change with ATP in their origin lane. In the on-ramp scenario the interaction between lane changing vehicles and the ATPs in their target lane is simulated.

For the off-ramp 'off-ramp 22 on the A16 going south' is chosen. This off-ramp is on the main corridor Rotterdam-Belgium. It is the first off-ramp when leaving from the Maasvlakte that is directly connected to main carriageway. Due to it being very close to the Port of Rotterdam it contains a very high truck share. This is useful because it will enhance the effect that the ATP shows.

For the on-ramp the connection 'A15 going west-A16 going south' in the intersection 'Knooppunt Ridderkerk-zuid' is chosen. This is the first on-ramp that directly connects to the main carriageway in the truck corridor Port of Rotterdam-Belgium. The section also contains a very high truck share on the main carriageway.

5.1.3. Tactic selection, making lane changes

ATPs making unconflicted lane change[8] are not considered, because tactics to accomplish these are trivially easy. This means that in this research only the conflicted lane changes are examined. To do this again an on-ramp is selected because on-ramps sections isolate unidirectional lane changing.

5.1.4. Road section selection, making lane changes

The selected on-ramp is the on-ramp 'Gaderingviaduct – A15'. This on-ramp has an extreme truck share of nearly 50%. This effect of ATPs becomes very apparent in a simulation based on this section.

5.2. Scenario design

In this paragraph different design decisions are presented. All these decisions apply to all the simulation network designs. Firstly, in this chapter the choices on which scenarios are modelled are presented. This is done based on expectations of influential factors to the lane change location of vehicles. After that a subparagraph with non-spatial decisions and a paragraph on spatial decisions made in the scenario design process are presented.

It is expected that the effect on lane change location is influenced by multiple causes of which many have correlation with each other. This can be represented in a simplified conceptual manner:

$$D(d_{lanechange}) = \sum_i \left(\sum_i f(p_i) * \prod_i f(p_i) \right)$$ Equation 37

In which $D(d_{lanechange})$ is the lane change location distribution. When attempting to describe the actual shape of Equation 37. It requires at least three (preferably more) data points per parameter p_i in each dimension i ($n_{x\ per\ i} = 3$). Note that increasing the dimensions also increases the complexity of Equation 37 and acquiring one data point has a cost of about three days' worth of simulations ($t_{perpoint} = 3$). This results in a total simulation time in days of:

$$T_{sim} = t_{perpoint} * (n_{x\ per\ i})^{n_p}$$ Equation 38

In which n_p is the number of parameters. If one is interested in five parameters this would already result in 729 days of simulation. This small example shows how quickly simulation time can get out of hand. To be able to give meaningful conclusions about $D(d_{lanechang})$ one has to reduce the simulation time and make assumptions on the shape of Equation 37 and/or reduce the amount of parameters that are regarded as dimensions. If one would simplify Equation 37 with the assumption that each parameter has an effect that is uncorrelated with the effect of the other parameters. One could simplify it to the following:

$$D(d_{lanechange}) = \sum_i f(p_i)$$ Equation 39

This massively reduces complexity and would reduce the simulation time to:

[8] A lane change into an empty lane

$$T_{sim} = t_{perpoint} * n_{x\ per\ i} * n_p \quad \text{Equation 40}$$

With this approach the simulation time now scales linear with the number of parameters, and each chosen parameter would add 3 days to the simulation. It also limits the research to parameters that one can defend to be uncorrelated. Sadly, not all parameters are uncorrelated, all parameters are heavily correlated with location j. Therefore, a middle form is chosen for this research in the shape of:

$$D_j(d_{lanechange}) = \sum_i f_j(p_i) \quad \text{Equation 41}$$

With a simulation time of:

$$T_{sim} = t_{perpoint} * n_{x\ per\ i} * n_p * n_j \quad \text{Equation 42}$$

In the remainder of this chapter a selection is made which parameters to include in simulations and which are set as constants. They are described in two categories the spatial and non-spatial. Spatial parameters have to do with the physical space that is represented in the model. The non-spatial parameters have to do with everything else, e.g. traffic demand (per direction), truck share, penetration rate of ATP vehicles, etc.

The choice on which non-spatial parameters become variables is discussed in 5.2.1. The decisions made on the general spatial design are discussed in 5.2.2, however this does not include the final designs, those are discussed in 5.3.

5.2.1. Non-spatial design decisions

In this subparagraph, choices on handling the non-spatial parameters are presented. These mainly regard the usage of the ATPCM**,** details regarding road intensity and amount of hours simulation time per simulation case. First the choices on the usage of the ATPCM are put apart followed by the details regarding road usage and lastly the simulation hours are addressed.

The ATPCM is an estimation of what would be possible. This makes that the design will most likely never be implemented in a real truck. The calibration of the parameters is extremely uncertain. To cover this uncertainty, one could add a 'range of designs' by changing calibration parameters such as the following distance, the behaviour of the collision avoidance and the length of an ATP. But each change will add a dimension to the overall problem and thus increase simulation time.

If one would try and create a range of ATP models to assess, the choices on which parameters to vary and which to keep constant are not evident at all. Therefore, in this research only one type of ATP model is considered. This will give initial ideas on the effects but leaves a demand for redoing the investigation when the actual algorithms that are implemented in the ATP are known.

About road usage, a basic method to describe the road usage is a multi-mode O-D matrix, which contains all vehicle types going from one place to another. Implicitly the O-D matrix contains many parameters such as truck share, penetration rate, 'the share between main carriageway intensity and acceleration lane intensity', etc. Conclusions based on these parameters are more meaningful than conclusions based on a specific O-D matrix due to the applicability in other scenarios. However, the applicability of a conclusion from one location to another is a pseudo truth. It seems true, but the fallacy made is ignoring the correlation between the parameters that all find their origin in the O-D matrix.

To accomplish multi applicable conclusion it is assumed that the effect of ATPs has on $D(d_{lanechang}\ )$ depends on whether a driver encounters an ATP while merging. Many of the parameters that find their origin in the O-D matrix contribute to this. To prevent any correlation errors only one of the parameters is chosen as a variable. This variable now mainly represents the encounter rate, but also, of course, represents itself. The parameter chosen as a variable is total demand.

This means that truck share (per stream), penetration rate and the share between streams should all stay constant for a certain location. The value on the value of these parameters are extracted from an average morning peak according to the INWEVA 2017 data set. Note that in a simulation only one stream contains an ATP, due to the inability of the driver model to handle merge behaviour between two ATPs. The variance in the total demand is set to three settings, an average morning peak (usually around 40-50% capacity) 70% capacity and 80% capacity. It is chosen not to go closer to capacity because the ATP controller's CACC function does not work properly with speeds under 65 km/h. The capacity values are determined based on 'Handboek Capaciteitswaarde Infrastructuur'[63].

About simulation hours, it is common practice to do multiple runs per simulation case. Having multiple runs gives two distinct upsides. Firstly, whenever the traffic state in a simulation gets influenced by spillback effects due to rare events (or bugs) in the simulation the traffic state will receive a reset and not pollute the full dataset. Secondly, each run in a set of multiple runs can be viewed as a unique estimation of the actual "true" outcome. Having multiple runs opens the option to do statistical analyses on the different runs. In this research 10 runs per simulation case are chosen, each run consists of 2 hours of morning peak traffic. In case the accuracy of an estimation needs to be higher, extra runs can be executed.

5.2.1.1. A platoon of three identical vehicles

In this paragraph different design choices are presented and explained. Firstly, the reasons to reduce the research to only three-vehicle-platoons are presented.

The ATPCM which is created especially for this research was always meant to be a general basis, ready for expansion. Therefore, the model is created in such a way that it was easy to adjust for other studies and easy to implement in different VISSIM scenarios. To make the model easy to implement, the choice has been made to make it work by adding a single ATPCM to the VISSIM model. The upsides of this choice are easy implementation and reduced development time. The downside of it, however, is that the ATPs are limited to a single length, and the model should be able to differentiate the role that a vehicle has within its ATP.

The length of an ATP is limited to three vehicles in this research. The reason for this is, three is the minimal length for an ATP in which at least one vehicle does not need a driver. A second reason, three vehicles per ATP make direct communication between vehicles possible within VISSIM. Vehicles in VISSIM can only request data of other vehicles that are to two vehicles in front or behind and in the relative lane l or $l-1, l-2, l+1, l+2$. This result to a limit of maximum 20 vehicles, but the spatial limitations result in an ATP of three vehicles, if direct communication is a demand, which it is, to simplify the implementation process of the longitudinal behaviour.

5.2.1.2. Platoon formation

In both paragraph 4.2 and 4.3 it is assumed that an ATP is already formed. In the model however, vehicles spawn one by one. This means they are not spawned as ATPs, this means some method must be designed to create an ATP at the start. Apart from that, if for any reason an ATP would break up, it should be able to connect back together.

To spawn an ATP, a ramp meter is proposed that is placed on a dedicated lane for ATP vehicles. The ramp meter will let only three vehicles through. And the ATPs are spawned in the same semi random way as all the vehicles in VISSIM are spawned, which will result in a realistic distribution of ATPs over time.

To accomplish reforming ATPs after break-up, a connecting longitudinal state is introduced. Whenever an ATP does not consist of three vehicles and there is a vehicle n behind the ATP that could connect, the leader of the ATP will change its desired speed to 90% of the desired speed of vehicle n until vehicle n is connected to the ATP.

5.2.2. Spatial design decisions

The main spatial decision for a simulation is the location choice, however that has all been covered in paragraph 5.2. In this paragraph the other design decision on the spatial layout of the simulation are presented. These include:

- The method to measure the location of a lane change
- The method to create more realistic on-ramp behaviour
- The method to create a stream containing both normal vehicles and ATPs

Each subject will get its own sub paragraph.

5.2.2.1. Measuring the location of a lane change

Based on van Maarseveen 's [15]** findings it is expected that the lane change location will shift further downstream on the acceleration lane. At high intensities it is even expected to overshoot the acceleration lane. In VISSIM however, it is not possible to model overshooting an acceleration lane without losing the 'urgency' part in the model. This is because vehicles will base their urgency on the distance to the emergency stop and a vehicle can never pass the emergency stop.

Because measuring the exact distance of lane changes has a higher priority than the urgency part of the model, the simulation has extreme long on-ramps of 1500 meter. Losing the urgency part in the model, though, will greatly decrease the validity of the actual lane change distances. Instead the only thing that is measured in these simulations is the lane change distance when no one ever feels urgency or stress related to the end of an on-ramp. This will have a large impact on which conclusions can be drawn from the results.

5.2.2.2. Realistic on-ramp behaviour

In VISSIM the velocity of vehicles on the on-ramp is equal to the velocity of the vehicles on the acceleration lane. This causes the merge location to be very far near the end of the on-ramp. A possible explanation for this is that the amount of presented gaps is small when vehicles move at the same distance. Apart from the number of gaps presented, the equal speed also causes the *Deadlock of advanced merging* (subparagraph *3.1.2.2*) to occur very frequently.

A way to solve this unrealistic acceleration lane behaviour, the findings of Kolen [52]** are used to create a more realistic desired velocity on the acceleration lane. Kolen presents an empirical analysis of the speed of vehicles on on-ramps (Image 16). His findings show that vehicles do not accelerate or decelerate much after the last 20 meters on the acceleration lane. He also presents a distribution of the speeds during merging.

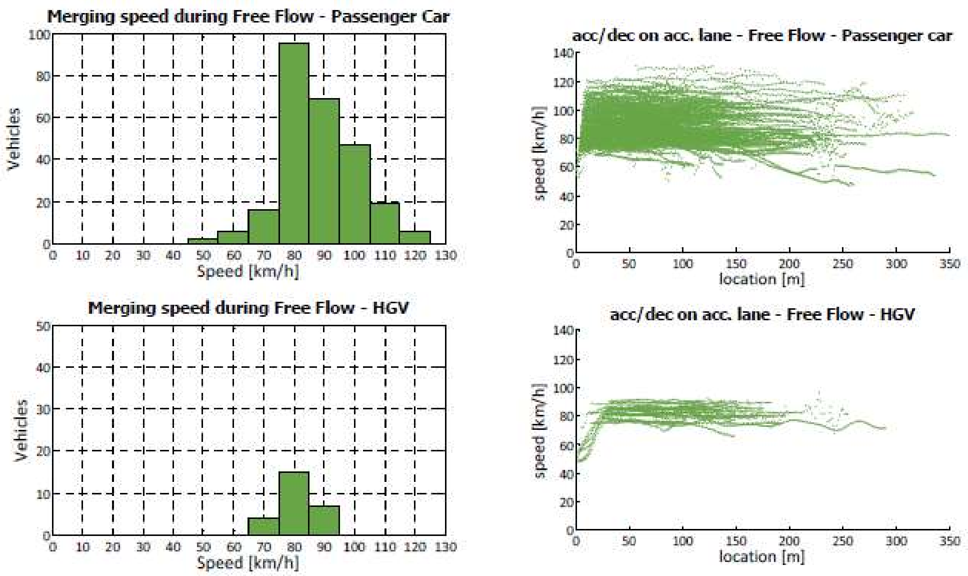


Image 16 Acceleration lane velocities (copy of Kolen[52])**

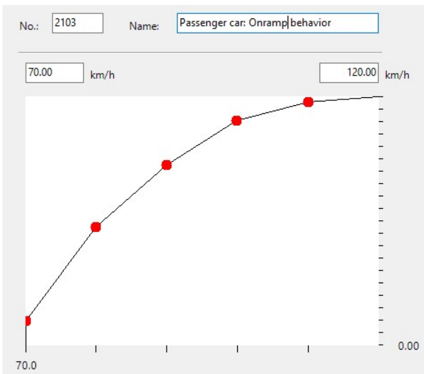


Image 17 Desired speed distribution

To implement the findings of Kolen into the VISSIM model, a method must be found to create different behaviour on different ***lanes***[9] of the same ***link***. The proposed method of the developers of VISSIM is by changing ***vehicle types*** of vehicles that merge using the COM server. However, this method is very time consuming to implement and a different method has been applied. To change the behaviour of the vehicles on the on-ramp, their ***desired velocity*** is changed to the distribution found by Kolen and changed back to a normal motorway ***desired velocity*** after entering the main carriageway. This is done by adding a large amount of ***desired speed decisions*** (equivalent to traffic signs) on the far-right lane of the main carriageway. An example of this is shown in

[9] ***Italic Bold*** words on in chapter 5 refer to definitions from the VISSIM software package

Image 18, note that all the yellow lines represent a ***desired speed decision***. The distribution is inserted in VISSIM is shown in Image 17.

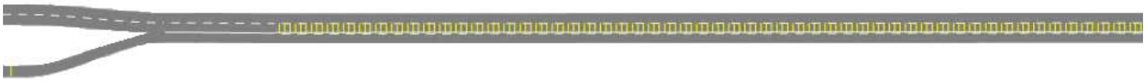


Image 18 Lane change decisions on entering the motorway

5.2.2.3. Creating a stream with normal vehicles and ATPs

As is described in paragraph 5.2.1.2, ATPs spawn on a dedicated lane. When measuring the merge locations, however, the ATPs should be in the traffic mix of the main carriageway. A method must be designed that creates the proper traffic mix before the on-ramp section is reached. There is a risk that when ATPs would merge into the mainline, the main carriageway will get congested and therefore the traffic mix is different from what it was supposed to be.

To prevent this risk from happening instead of merging the ATPs using an acceleration lane, a lane with ATPs is added as the far-right lane of the main carriageway, and after 1500 meters the far-left lane is dropped. An example of this is given in Image 19.

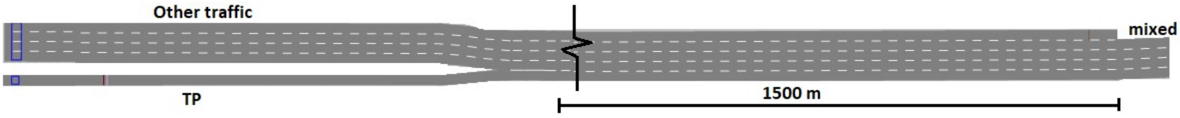


Image 19 Creating mixed traffic

5.3. Specific designs

In this paragraph for each location chosen in paragraph 5.2, the section is represented by a map of the location, a schematic of the section, capacity values based and an O-D matrix. Note that in the schematic the line at which capacity is determined is also drawn. The naming of the design is based on what situation is measured and not the name of the location.

5.3.1. Design ATPBON: an Automated Truck Platoon Blocking the ON-ramp

For this design the location: 'A15 going west-A16 going south' in the intersection 'Knooppunt Ridderkerk-Zuid' is chosen. The context of this section is given in Image 20, the schematic is given in Image 21 and data regarding the average morning peak and the capacity are given in Table 7.

Image 20 Design ATPBON: Location

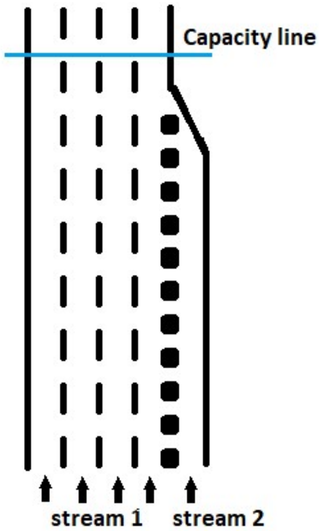


Image 21 Design ATPBON: schematic

Table 7 Design ATPBON: information on demand

	Stream 1	Stream 2	Capacity line
Average morning peak Intensity	4389	764	5153
Capacity flow	6984	1216	8200
Truck share	7,10%	19,31%	8,91%
TP Penetration rate	30%	0%	

5.3.2. Design ATPBOFF: an Automated Truck Platoon Blocking the OFF-ramp

For this design the location: 'off-ramp 22 on the A16 going south' is chosen. The context of this section is given in Image 22, the schematic is given in Image 23 and data regarding the average morning peak and the capacity are given in Table 8. Note that for taking an off-ramp, a vehicle can already plan and make sure it is in the far-right lane. Within this model, a vehicle will notice that its off-ramp is coming 1600 meters before the actual off-ramp appears. 1600 meters is chosen because this is the distance in which the first sign appears on the Dutch Motorway.

Image 22 Design ATPBOFF: Location

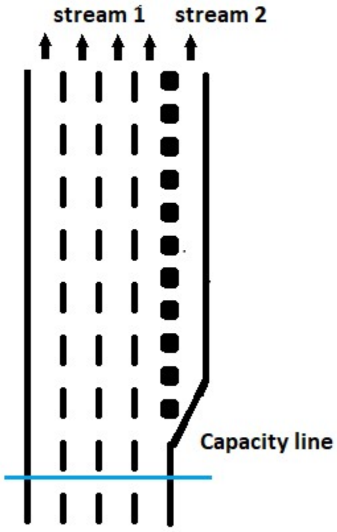


Image 23 Design ATPBOFF: schematic

Table 8 Design ATPBOFF: information on demand

	Stream 1	Stream 2	Capacity line
Average morning peak Intensity	5188	344	5532
Capacity flow	8690	510	8200
Truck share	8,95%	32,99%	10,45%
TP Penetration rate	30%	0%	

5.3.3. Design ATPOON: an Automated Truck Platoon On the ON-ramp

For this design the location: 'on-ramp Gaderingviaduct – A15' is chosen. The context of this section is given in Image 24, the schematic is given in Image 25 and data regarding the average morning peak and the capacity are given in Table 9.

Image 24 Design ATPOON: Location

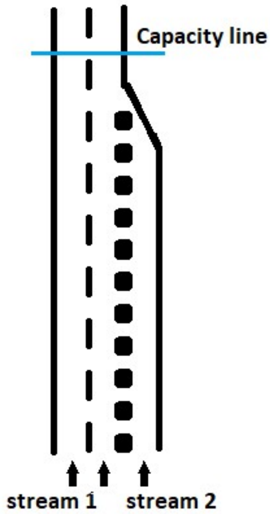


Image 25 Design ATPOON:

Table 9 Design ATPOON: information on demand

	Stream 1	Stream 2	Capacity line
Average morning peak Intensity	1831	357	2188
Capacity flow	3515	685	4200
Truck share	7,92%	49,23%	14,65%
TP Penetration rate	0%	30%	

5.4. Simulation visualization

In this paragraph the simulation and the data gathering are visualized. Firstly, the network designs containing on-ramps are described followed by the network design with an off-ramp.

5.4.1. Visualization of simulation networks containing an on-ramp

In the simulation an ATP blocks an on-ramp (ATPBON) vehicles will merge from an on-ramp into the main carriageway. At some moment every vehicle that makes a lane change will cross the line with the middle of the front of the vehicle. During this moment the longitudinal location of the front of the vehicle is marked as the lane change location for that vehicle. This means that every vehicle has only one lane change location per lane change. In Image 26 an example is shown of a grey and a blue vehicle that are both exactly at their lane change location, the two-coloured lines and the number line represent the value of the lane change location of the vehicles.

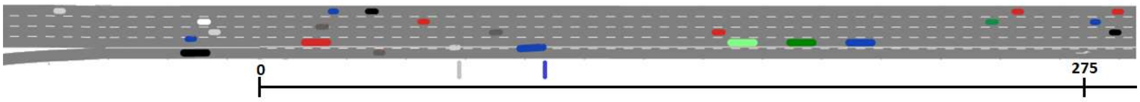


Image 26 Lane change location (in meters from the start of the on-ramp)

When introducing ATPs to the system, a situation can occur where an ATP blocks off some other vehicles. In Image 27 an example of such a situation is given, note that an ATP is represented by a blue leader with two different green followers. This ATP blocks of a white, black and grey vehicle.

Because the vehicles that are blocked off the main carriageway need time to pass the ATP or let the ATP pass them, the lane change location of these vehicles is further downstream than it otherwise would be. Sometimes vehicles that are blocked can still make their lane change within the normal on-ramp length of 275 meters. An example is given in Image 28. However, it is not uncommon for vehicles to be unable to make the lane change within 275 meters as can be seen Image 29, where three vehicles on the on-ramp passed the 275 meters mark.

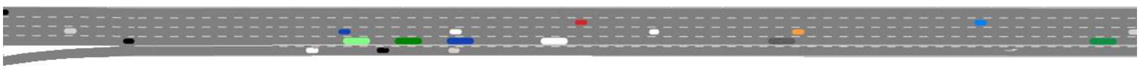


Image 27 An ATP blocking merging vehicles

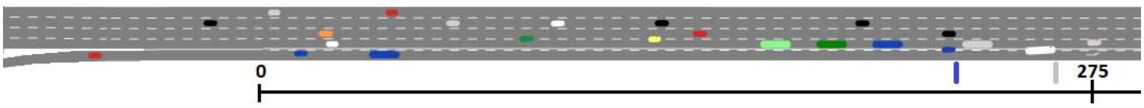


Image 28 Vehicles merge just in time (lane change location, in meters, from the start of the on-ramp)

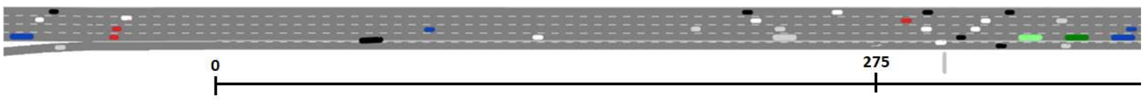


Image 29 Vehicles merge to late (lane change location, in meters, from the start of the on-ramp)

To measure the effects of ATPs on the lane change locations of the vehicles, a base case without ATP and one with mixed traffic is run. For both simulations all the lane change locations are gathered. When plotting the lane change location in a fine meshed histogram it will yield a distribution. An example of such a distribution is given in Image 30. Comparing the distribution of the base case with that of the one with mixed traffic will yield insight into the effect ATPs have on lane changes.

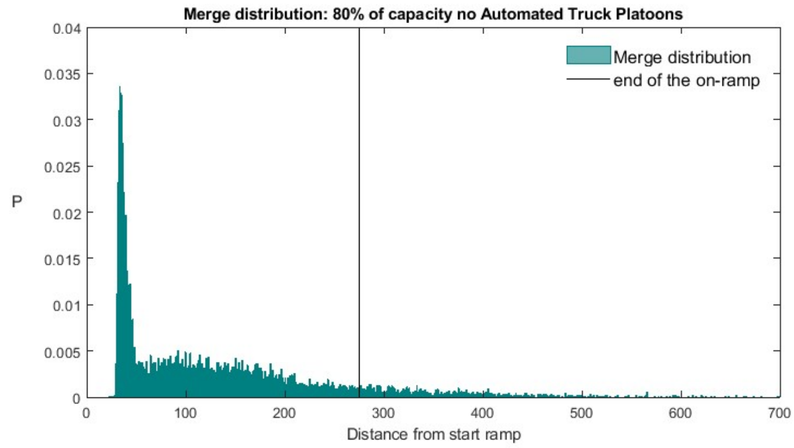


Image 30 Example of a merge distribution

In the simulation where an ATP starts on an on-ramp, the lane change location of both the conventional and the ATPs is measured. Note that one ATP has three different lane change locations, to illustrate this in Image 31 a lane change of an ATP is illustrated using a snapshot of two timesteps. The first timestep illustrates the lane change location of the rear vehicle and, six seconds later, the second timestep illustrates the lane change location of the leader and middle vehicle. The bar below the section illustrates the data that are saved of this lane change by this ATP.

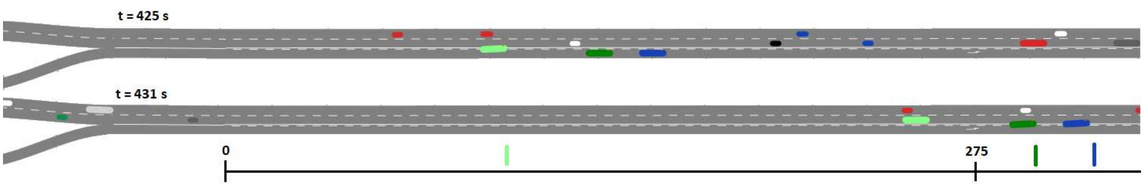


Image 31 The three lane change locations of one ATP

5.4.2. Visualization of simulation networks containing an off-ramp

Equal to the definition of a lane change location in a section with an on-ramp, a lane change location in a section with an off-ramp is measured from the moment that the new lane change option becomes available. In the simulation it looks as in Image 32.

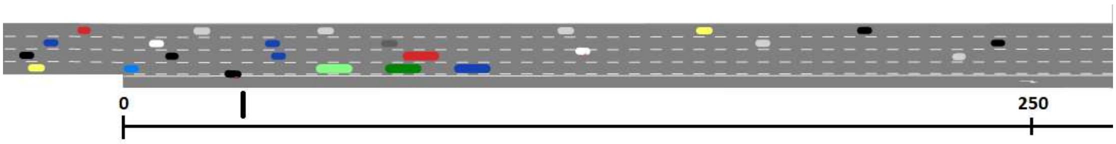


Image 32 Lane change location on an off-ramp

5.5. Accuracy and Precision

In this paragraph the error term in the model results is discussed. Also, the nature of the error term is described, “what influences precision (how varied the results are per simulation run)?” and “what influences accuracy (how well does the results describe reality)?”.

When describing human driving behaviour in a model, the detail of the model heavily influences the accuracy and the complexity of the model. Often more sophisticated models mimic human behaviour in a detailed manner, which includes a high variance in behaviour. The better the human is described in the model, the more accurate a model can be, but adding the humanlike high variance heavily reduces the precision of a model.

Due to the nature of models and human behaviour, one cannot quantify the accuracy of models in terms of confidence intervals. However, one can quantify the precision of a model. To make a model more precise more data must be gathered from the model.

A more precise result means that one can be more certain that the model does predict one’s conclusions, however the conclusions are limited in accuracy to the extent that the model accurately describes reality.

In the results chapter of this research some error margins are given, these represent the margin of error of the models and therefore describe only precision. They cannot be interpreted as the margin of error in describing reality.

5.6. Verification

In attempt to verify the models, the base case of the models is compared to research on the merge location of vehicles on Dutch Motorway on-ramps, for offramps no research has been found. Therefore, in this chapter only the verification of the on-ramp models is discussed.

To verify the models the base case scenarios are compared with the finding of Daamen, Loot and Hoogendoorn [51]. In 2010 they did an empirical analysis on motorway on-ramp behaviour and one of their findings was a merge location distribution (Image 33).

Their findings are compared to the base scenarios of an average morning peak in simulation designs that contain an on-ramp. Those are network design ATPBON and ATPOON. The difference between the distributions is made visible by means of a cumulative curve, which is presented in Image 34.

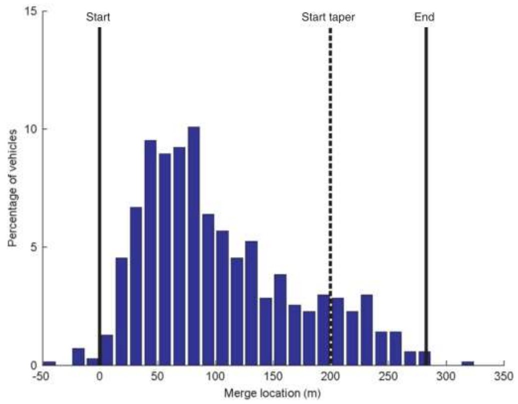


Image 33 Empirical findings on lane change locations (copy from Daamen *et al.* [51])

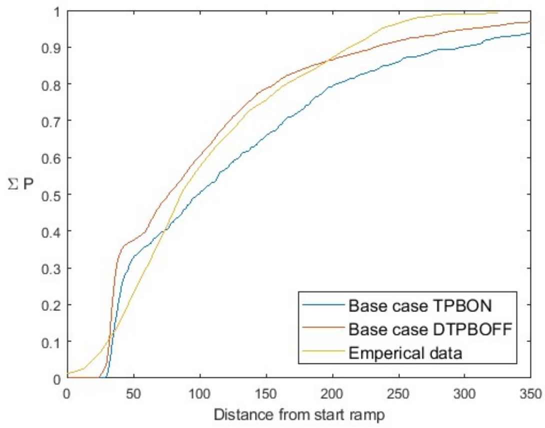


Image 34 Cumulative curve of merge locations

In both the simulations it is seen that the shapes of the cumulative curve for simulation models is quite different from empirical data. The model overestimates the number of vehicles that will do an almost instantaneous merge at the start of the acceleration lane. After that point the data of both simulations diverge therefore they are reviewed separately.

On ATPBON, after about 100 meters to 200 meters into the acceleration lane the model gives a quite accurate representation. After 200 meters this difference increases again. This is most likely the result of the long on-ramps used in simulation. Due to their length the driver model does not use the algorithms that mimic the stress related to reaching the end of the on-ramp.

On ATPOON, the cumulative curve of the simulation seems to always overestimate the merge location in comparison to the empirical data. However, there is doubt on the applicability of the empirical data for this specific design due to the extreme high truck share (49%) that is present on the acceleration lane in this network design. Daamen *et al.* [51] do not specify the truck share on the acceleration lane in their paper, though one can assume that if it had been as high as 49% they would have found it worth mentioning.

Concluding, Design ATPOON 's validity of the base case seems to be good for measurements between 100 and 200 meters on the acceleration lane. After that the model always gives an overestimation of the merge locations. On Design ATPOON, given (1) the validity of the base case in Design ATPBON and (2) the high truck share in ATPOON likely results in a longer distance to change lane, the base case of ATPOON is plausible.

6. Results

In this chapter the results of the effect study on lane change locations is presented. This is done by firstly explaining the methods used to interpret the data followed by a paragraph for each simulation network design.

The data are gathered by collecting the trajectory data. Merge distributions are obtained by collecting the location at which vehicles make a lane change. When reviewing a distribution on itself such a distribution can give insights. However, when comparing two distributions the difference is often difficult to observe. Therefore, out of these distributions cumulative curves are constructed. Cumulative curves make it easier to observe differences between distributions. [10]

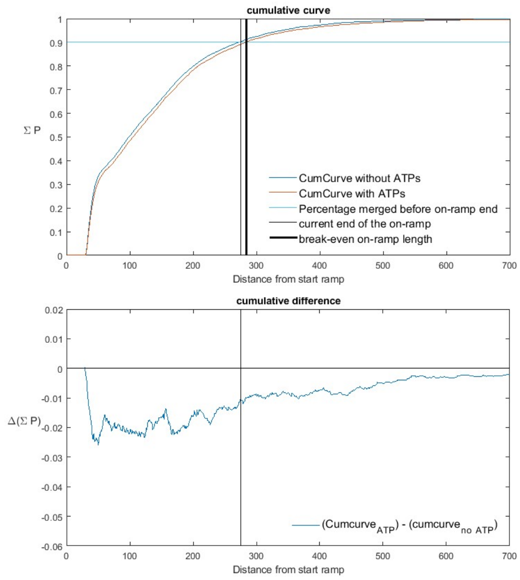


Image 35 Cumulative curve and -difference of ATPBON on an average morning peak (10 runs)

For the on-ramp cases, apart from the distributions, also key parameters are presented. These parameters are: 'the percentage of vehicles that merged before the end of the acceleration lane in the base case', 'the percentage of vehicles merged before the end of the acceleration lane when ATPs are present' and 'the break-even on-ramp length'. The break-even on-ramp length is the length that would result in the same percentage of vehicles merging before the end of the on-ramp as would happen in the base case. These parameters are chosen because they give insight into the effect of ATPs as well as give a prediction on which on-ramps these ATPs have less effects.

Next to the outcomes also the precision of the results is discussed, to quantify the precision the margin of error E is calculated (Equation 43). In this research a confidence level of 95% is kept resulting in a z value of 1,96.

$$E = z * \frac{\sigma}{\sqrt{n}} \quad \text{Equation 43}$$

For each network design a separate paragraph is presented.

6.1. Results of Design ATPBON: An automated truck platoon blocking the on-ramp

The initial amount of simulation runs for each scenario is ten runs of two hours morning peak. For the network design ATPBON, on an average morning peak demand, the model produces a cumulative curve as can be seen in Image 35. As can be seen in the graphs, in the base case, 90% of the vehicles can make a lane change before the end of the onramp whereas in case ATPs are present 89% of the vehicles can make a lane change.

[10] Enlarged graphs of the distributions and cumulative curves are presented in Appendix 4 to Appendix 7

The margin of error for both percentages mentioned above is 0,9% point. Which means that the 1% difference that is observed, is within the confidence interval of 1,8% (two times 0.9). Therefore, the model cannot significantly predict any difference with or without ATPs.

To get more insight in the blocking effect of ATPs near on-ramps, the number of simulation runs is increased to 50. This is based on the calculation in Equation 44. Using the standard deviation of the scenario with the highest standard deviation in the whole network design, it is determined that at least 42 runs were required to get a margin of error lower than 0,5% point.

$$0{,}5 < z * \frac{\sigma}{\sqrt{n}}, \qquad n > \left(1{,}96 * \frac{1{,}66}{0{,}5}\right)^2, \qquad n > 42 \qquad \text{Equation 44}$$

After 50 simulation runs the cumulative curves are as in Image 36, the corresponding mean, standard deviation and margin of error at the end of the onramp are presented in Table 10. As can be seen in Image 36, the effect of ATPs on lane changes is highest between 50 and 200 meters after the start of the ramp. As mentioned in the verification (paragraph 5.6) the model is most accurate between 100 and 200 meters after the start of the merging area.

The results show that, on an average morning peak, one in every 50 vehicles requires a longer distance than it would need without ATPs. During a crowded morning peak in which the demand is up to 80% of capacity one in every 25 vehicles requires a longer distance, due to the introduction of ATPs.

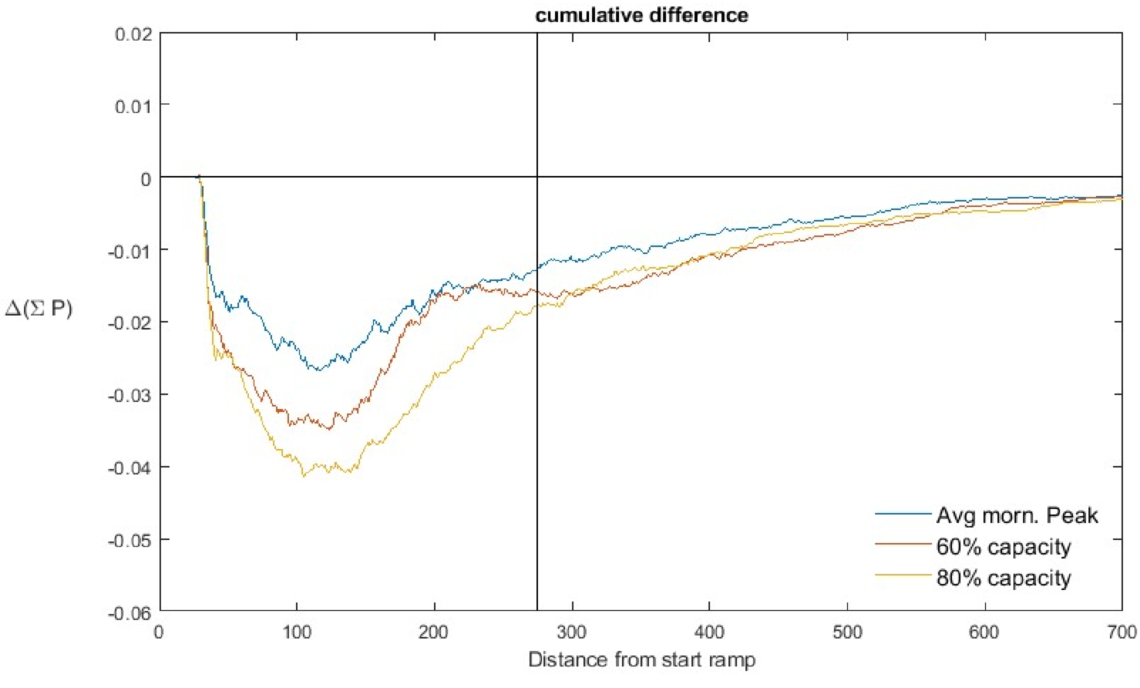


Image 36 Cumulative curves of all scenarios in ATPBON (50 runs)

Table 10 Distribution parameters and precision of the model for ATPBON with 50 runs (represented in %points)

Case	μ	σ	E
AMP[11] Base	90,23%	1,24%	0,34%
AMP with TP	88,97%	1,60%	0,46%
60% Base	89,77%	1,41%	0,39%
60% with TP	88,19%	1,53%	0,42%
80% Base	89,12%	1,29%	0,36%
80% with TP	87,36%	1,15%	0,32%

The findings on the number of vehicles that can make a lane change before the end of the ramp are presented in Table 11. As can be seen, the model estimates that 90% of the vehicles can make a lane change before the end of the on-ramp without having to break heavily or accelerate, this reduces a little to 89% in crowded situations. The results of the scenarios including ATPs show that the ATPs cause that 1-2% more vehicles are unable to make the end of the ramp. This means that in a crowded morning peak, one in every 25 vehicles requires more distance to lane change of which half of them requires more length than the on-ramp offers.

Table 11 Result summary of Design ATPBON with 50 runs

	Percentage of vehicles merged before end of acceleration lane; base case	Percentage of vehicles merged before end of acceleration lane; TP case	Breakeven onramp length
Average	90%	89%	+12m (287m)
60% capacity	90%	88%	+17m (292m)
80% capacity	89%	87%	+19m (294m)

If, equal to the base case, 10% of the vehicles can still make the ramp due to high acceleration or breaking heavily, the model predicts that during a crowded morning peak the negative effects of ATPs on lane changes can be negated by increasing the length of the merging area by about 20 meters.

6.2. Results of design ATPOON: An automated truck platoon on the on-ramp

In the scenario ATPOON two types of results are gathered. The results of the ATPs that need to change lanes, and the results of the conventional traffic using the same acceleration lane. The scenarios in the network design ATPOON have all been performed with ten runs of 2 hours of morning peak.

In Image 37 the cumulative curve of the lane change distribution during an average morning peak are given. As can be seen in the graph, the cumulative curves of the base case and those for conventional vehicles sharing their on-ramp with ATPs barely have any difference. This is also the case is the scenarios with 60% and 80% capacity. As presented in Table 12, in more crowded

[11] Average Morning Peak

scenarios a lower lane change location value can be found than in the scenario of the average morning peak. This lower value could be the result of vehicles slowing down when following an ATP and therefore earlier than they would if not following an ATP. Note that this difference is not significant enough to draw any conclusions from.

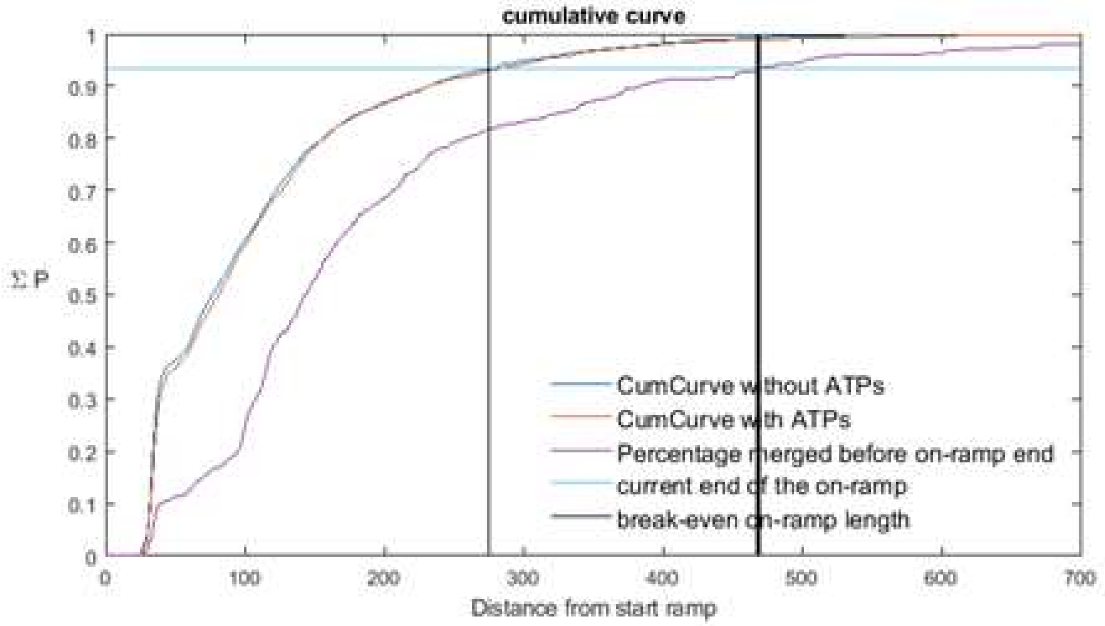


Image 37 Cumulative curves of ATPOON

Contrary to similarities of the conventional vehicles, the cumulative curve of the ATPs increases much more slowly. Also, the cumulative curve has a very different shape from the cumulative curves of the conventional vehicles. This difference in shape can be explained by the lane change tactic of ATPs. The cumulative curve is a distribution which is the sum of three distributions, one for each role in the ATP. The margin of error, standard deviation and mean are given in Table 13.

As can be seen in Table 12, between 18% and 28% of the ATP vehicles in unable to merge, this is much higher than that of conventional vehicles, which is logical because of the complex tactic that an ATP must perform to merge. However, when calculating how long an on-ramp should be to make it feasible for ATPs to merge the values become very large, up to 194 meters. This is most likely the case because of the long time it takes to create a large enough gap for the leader and middle vehicle to fit in. The model shows that when the traffic intensity increases the break-even on-ramp length does not increase with it. This could be because the model is not accurate in estimating very large on-ramp extensions.

Table 12 Result summary of Design ATPOON with 10 runs

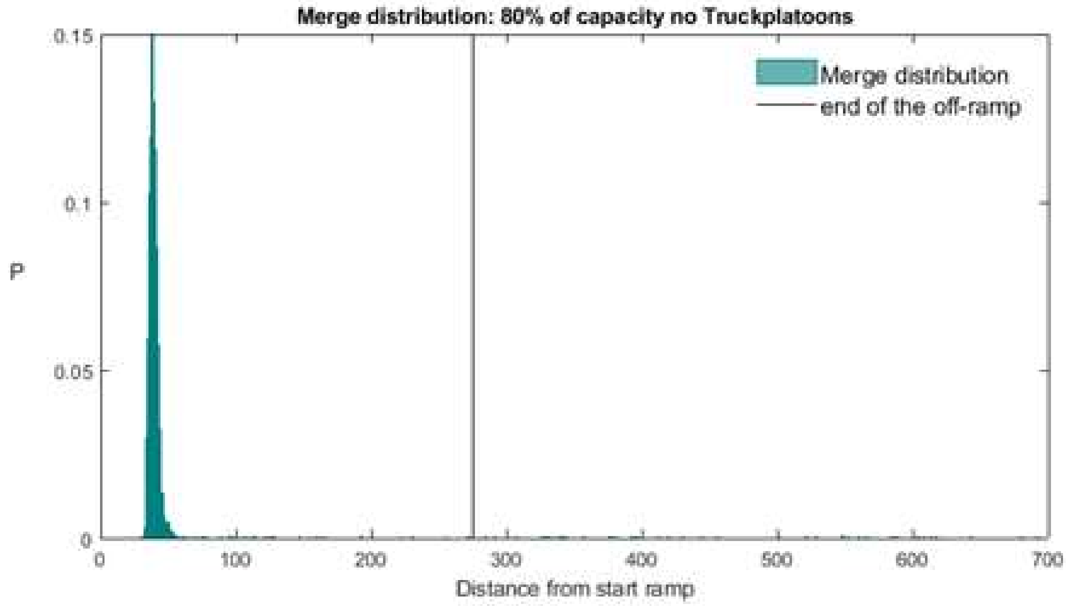
	Percentage of vehicles merged before end of acceleration lane; base case	Percentage of vehicles merged before end of acceleration lane; TP case	Break-even on-ramp length
Conventional vehicles			
Average	93%	93%	n/a
60% capacity	89%	89%	n/a
80% capacity	86%	87%	n/a
ATPs			
Average	n/a	82%	+194m (469m)
60% capacity	n/a	76%	+140m (415m)
80% capacity	n/a	72%	+160m (435m)

Table 13 Distribution parameters and precision of the model for Design ATPOON (represented in %points)

conventional vehicles				***ATPs***		
Case	μ	σ	E	μ	σ	E
base avg	93,26%	1,61%	1,00%	n/a	n/a	n/a
avg tp	92,85%	2,24%	1,39%	81,76%	8,78%	5,44%
base 60	88,83%	1,85%	1,14%	n/a	n/a	n/a
60 tp	89,23%	1,51%	0,93%	75,84%	8,23%	5,10%
base 80	86,25%	1,30%	0,80%	n/a	n/a	n/a
80 tp	87,49%	2,05%	1,27%	72,25%	10,84%	6,72%

6.3. Results of design ATPBOFF: An automated truck platoon blocking an off-ramp

The results of the design ATPBOFF are based on 10 runs of 2 hours morning peak. The distributions of the lane change location in the most crowded scenarios are presented in Image 38. As can be seen, most of the vehicles make the lane change very quickly after the off-ramp starts. In the other scenarios that are less crowded the distributions are almost equal. Given strict separation between discretionary and mandatory lane changes in the human driver model (as described in chapter 2), it is quite logical that most vehicles merge right at the start of the off-ramp. This is because for 1600 meters before the start of the off-ramp, vehicles will already have only mandatory lane changes to the right and ignore any change to overtake. The results therefore show no influence by ATPs.



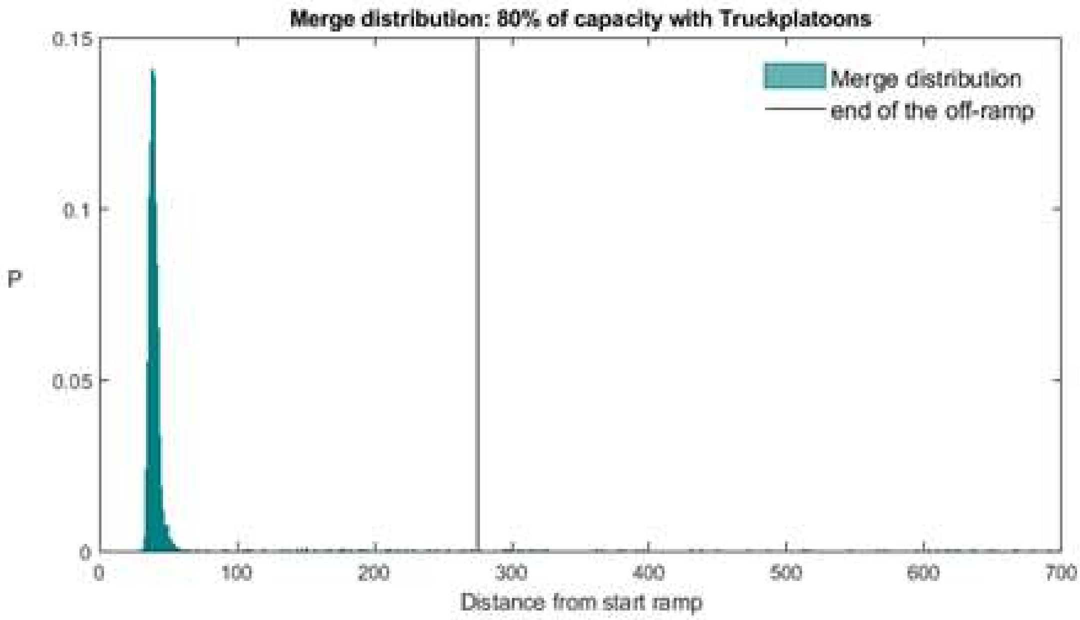


Image 38 Lane change location distribution of ATPBOFF

7. Discussion & Conclusion

In this chapter the limitations of the model are discussed and conclusions are presented. The conclusions are split in the research questions based on model development and research questions based on the effect study on lane change locations. Lastly recommendation for future research are done.

7.1. Discussion

The goal of this research was ***'develop a model which can simulate the effect automated truck platoons have on mandatory lane change locations on the motorways'***. In this paragraph the limitations of the model are discussed and the effect these limitations have on the results and conclusions of the effect study.

As any model, the applied model does not come without its limitations. For the driver model the Wiedemann car-following model is used combined with a much less validated and well described lateral model. When reviewing the lateral model, one can conclude that it is very far from human cognation and behaviour. The cause for this most likely is that a human has a gap selection process that takes much more time than a single simulation step, whereas simulations almost always decide for a single timestep based on data available in that single timestep. Because of this limitation the amount of time and distance a vehicle requires to make a merging manoeuvre is much longer in simulation. This either causes vehicles to stop at the end of the on-ramp or be deleted from the simulation at the end of the on-ramp. Neither of those options are suitable to measure how lane change locations change if an increase is expected. Therefore, removing the end of the on-ramp and making it as long as possible seems the only way to go.

This however weakens the lateral model even more, because it normally changes behaviour based on the distance until the end of the on-ramp. Results of the effect study, therefore, quite clearly show unrealistic behaviour for the base case for any data gathered passed $200m$ on the acceleration lane. However, both the simulation and the human driver make their decisions based on the gap size and the frequency of gap presentence. Therefore, the results are valuable as an indication for increased / decreased length for road sections that demand many tactics regarding mandatory lane changes. The results also can give an estimation on a break-even point, however, the uncertainty in how actual human behaviour will change this break-even point is quite large.

A second limitation of the lateral model is a strict separation between mandatory and discretionary lane changes. This causes the outcome the facilitation of unpredictable merges to be less unpredictable as one might expect in real life. However, if one assumes that a driver would be more cautious or less aggressive when encountering ATPs for the first time, the outcomes of the simulation of the off-ramp can be very realistic. However, there is uncertainty on whether these results will stay valid as drivers get more used to the interaction with ATPs. This should not be of mayor concern, though, because if drivers slowly get more aggressive towards ATPs they will do so with the current off-ramp length in mind.

The CACC that is implemented in the ATPCM did not yet have extensive testing, although it has been used in different TNO projects and still undergoes development. This creates uncertainty on the validity of the calibration settings of the CACC model. For this research that is not a large issue, because cut-ins do not exist inside the simulation, so the exact difference between the trucks within the ATP do not influence results.

The combination of this specific CACC algorithm in combination with Wiedemann as collision avoidance algorithm is a novelty. In this research heavy braking actions are extremely rare and thus such a validation of this novelty is not required because results will not be heavily influenced by changes. If one would use this model to research scenarios in which many braking actions are expected, the collision avoidance must be defined in a different manner.

The ATPCM has been designed in a manner that would make adding features easy. The main reason for this was to be able to implement lessons learned during development without having to do large parts of the programming over again. The result is an ATPCM in which different control regimes can be activated based on action lines and driver states. This causes the model to be widely applicable for different CACC purposes, also those that do not contain trucks. However, the way the collision avoidance is implemented results in the applicability of the ATPCM only on roads on which the average velocity is over 70 km/h.

7.2. Conclusions on model development

Question 1: *Which driving models are suitable for conventional traffic, considering the interaction with automated vehicles?*

Longitudinal models are much further developed than lateral models, this causes the models that measure lane change specific problems, such as being less accurate than models that only include longitudinal behaviour. However, in the last decade much improvement has been made in this field.

When considering the interaction with automated vehicles, little behavioural change is expected, therefore little difference in the models is required. The improvements that can be made have to do with either conventional vehicles are likely to drive more slowly on the acceleration lane, or the gap acceptance will become smaller in case there is interaction with an ATP.

Question 2: *Which known driving / control algorithms (sub models) are suitable to model ATPs?*

For longitudinal behaviour: all found ATP simulations from other studies that model interaction with conventional vehicles use a CACC algorithm as a car-following method. The difference lies in the implementation of the collision avoidance and the detail in which the separate vehicles of an ATP are modelled.

In this research for the followers in an ATP, the CACC design of Ploeg *et al*. is chosen because the input parameters of that model are easily calculated within the simulation environment. As collision avoidance system, the breaking state of Wiedemann is used.

As control model for the leader the longitudinal parts of the Wiedemann model are chosen.

For lateral behaviour the lateral control is adopted from the Wiedemann lateral model, as well as the gap acceptance in which a vehicle will make a lane change on its own. However, for an ATP changing lane as a whole no prior designs were found and therefore a novel one is designed.

Question 3: *How can driving / control algorithms form a full-scale ATP control model?*

To create a full-range ATCM, the ATPCM should be able to do a role determination to deduce its position and function within the ATP.

For longitudinal control the ATPCM should also do a state determination which determines the driving state (e.g. free-flow, CACC flowing, heavy breaking). If CACC is used as the algorithm in the car-following algorithm, a collision avoidance algorithm should be added. Whenever $a_{wiedemann} < -2{,}5\ m/s^2$ the collision avoidance state is active, and the model will use $a_n = a_{wiedemann}$.

For lateral control three distinct categories must be addressed: (1) the lateral movement (2), the lane change decisions for an ATP as a whole and (3) lane change decision for a single vehicle. The lateral movement of each vehicle is adopted from the default in VISSIM. The lane change decision for the ATP is managed by the leader of the ATP. Equal to reality, in the model, The lane change decision for the ATP as a whole is managed by the leader of the ATP. The lane change decision of a single vehicle is based on the ATP lateral model which is designed in this research.

7.3. Conclusions on effect study

Question 4: *In which road sections is an effect expected on lane change location due to the presence of ATPs?*

ATPs need to be able to execute the following tactics:

- Facilitate a mandatory predictable lane change from the right and left.
- Facilitate a mandatory unpredictable lane change from the right and left.
- Make a simple lane change to the right.
- Make a mandatory conflicted lane change to the right and to the left.
- Make mandatory weaving manoeuvre to the right and to the left.

During these tactics there are interactions with the lane change manoeuvres of other vehicles and those of ATPs. Therefore, they could conflict one another, the manoeuvres with most apparent conflicts are:

- Facilitate a mandatory predictable lane change
- Facilitate a mandatory unpredictable lane change
- Make a mandatory conflicted lane change

The sections in which these conflicts become most apparent are:

- Onramps and off-ramps
- Joining and splitting carriageways
- Weaving areas

Question 5: *How do lane change locations differ due to the presence of ATPs?*

To measure the effect of ATP on road sections, the tactics that are required in the road sections are simulated in a separate simulation network designs. The sections are then reviewed considered the result of ATPs during the tactics required in that section.

To measure the effect of each tactic will now be addressed in a separate paragraph, followed by a separate paragraph for the consequences this has on the road sections mentioned in the answer to question 4.

7.3.1. Facilitate a mandatory predictable lane change

Based on the results of the simulation ATPBON, it can be concluded that on an average morning peak 1 in every 50 vehicles requires a longer stay on the acceleration lane in order to make its lane change, half of the vehicles is unable to make this lane change before the end of the acceleration lane. In a crowded morning peak containing an intensity of 80% of capacity, the problem is doubled to 1 in every 25 vehicles requiring more distance and half of them unable to make the merge before the end of the acceleration lane.

In order to create a situation in which all vehicles can merge safely the acceleration lane requires to be extended up to 300 m, this is an extra 50 m above the current RWS guide lines for Motorway design [1]*.

7.3.2. Facilitate a mandatory unpredictable lane change

Based on the results of the simulation ATPBOFF, it can be concluded that ATPs have no influence on the unpredictable lane change. One could argue that this is a model artefact based on the strict separation between discretionary and mandatory lane changes in the human driver models, however it is argued here that it is likely for vehicles to be more reluctant to overtake an ATP if they expect a risk not to make the lane change in time, therefore the model is quite accurate.

7.3.3. Make a mandatory conflicted lane change

In case ATPs would need to merge into the motorway while in an ATP formation, the length of the required gap to make a merge is much longer than the current acceleration lanes. Estimations show lane changes take over 400 meters to complete. One could argue that this is far outside of the precision range of the model, which it is, but the most important part of this conclusion is not the exact value of 400 meters, but that this value is >>275 m which is the current on-ramp length.

The consequences of the tactics on the road section are as follows:

7.3.4. On-ramps and off-ramps

On on-ramps, ATPs create a barrier between the merging traffic and the target carriageway. This causes the merge locations to shift further to the end of the on-ramp. It is estimated that if an ATP blocks the on-ramp, a vehicle needs up to 300 meters to get around the ATP, note that these 300 meters is an upper boundary and it is possible that the effect of ATPs is smaller.

On off-ramps, no negative effects of ATPs have been found for normal traffic. In case the off-ramp is part of an intersection, it is possible that the ATP will take the off-ramp in formation. The distance an ATP needs for this is not estimated, but it is assumed to be smaller than the distance an ATP needs for a conflicted lane change. Therefore, this distance is smaller than 400 meters. In case off-ramps are designed to be taken by ATPs, the lane change section should be reviewed.

7.3.5. Joining and Splitting carriageways

When carriageways join, the possibility occurs that an ATP needs to make a conflicted lane change to get back into the rightmost lane. Given that it is estimated to take 400 meters per lane to make such a manoeuvre joining carriageways must be reviewed to make sure that a truck that is a member of an ATP is still able to reach all possible directions. E.g. an off-ramp cannot be 600 meters downstream of a 2x2 joining carriageway.

The RWS motorway design guidelines [1]* suggest a 150 meters of blocked markings a carriageways splits before the actual split. Given that an ATP needs much longer to perform a lane change this design guideline does not give the other road users sufficient information when they must interact with an ATP. Therefore, it is advised to change this guideline to 400 meters.

7.3.6. Weaving areas

The conflicts that occur in a weaving area usually contain a combination of two or more lane change related tactics. This makes the estimation of the distance an ATPs requires to accomplish its own tactic difficult. Where the upper boundary of the length an ATP needs is 400 meters, the interaction with other lane changing vehicles can increase this. This can be represented by the equation:

$$d_{lanechange} = 400 - \varepsilon_{overestimate} + \varepsilon_{interaction\ penalty} \quad \text{Equation 45}$$

In which ε describes the estimation errors.

Because the extend of the over estimation is unknown and the penalty on the interaction is unknown, the lane change distance in weaving areas remains unknown. With a rough estimation being somewhere around 400 meters.

7.4. Future research

A possible path for further research, are the traffic impacts of ATPs using variable merge section lengths. This research would require a well validated and calibrated lane change model. But there is great value in having a good estimation on relation between merge length and ATP interaction. This will contribute greatly to a cost benefit analyses on potential adjustments to the road layout in favour of ATPs.

A different path is fine tuning the estimations for merge location distributions for different network parts, especially for weaving areas. To this however a driver model is required that contains a much more sophisticated lane change model than the driver model used in this research.

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Appendix 1 CACC algorithm (Confidential)

Removed due to confidentiality of the content

Appendix 2 Ramp meter algorithm

The ramp meter algorithm used for this research is an adaption in VBA of the Matlab file MAIN_TestCOM8.m which is written by A.M. Salomons (TU Delft).

The algorithm is a control algorithm for a single signal group. The algorithm will keep the signal group in red. When the queue is long enough, it will create green time sufficient for three vehicles to pass.

A queue in VISSIM is not formulated statically. Vehicles can enter and leave a queue. Vehicle n will become a queue whenever it has a velocity of less than 5 km/h. Vehicle $n-1$ will join the queue if n is a queue, $v_{n-1} < 5\ km/h$ and $d_{n-1} < 20\ m$.

If any vehicle i has a velocity of $v_i > 10\ km/h$, it will leave the queue. And if vehicles will both vehicle n and $n-1$ form a queue, if the headway $d_{n-1} > 20m$, then the queue will split in two queues of one vehicle.

In VISSIM, queue meters can be implemented. A queue meter is an object placed on a link that will measure the first queue upstream of its location. If a signal head and a queue meter would be placed almost at the same location, a queue meter will measure the queue length at the signal head. This interaction is used as input for the following algorithm.

IF QueueLength > QueueLengthOfThreeVehicles

    Signalstate = “Green”

    TimeBackToRed = TimeNow (t)+ GreenTime

END

IF TimeNow == TimeBackToRed

    Signalstate = “Red”

END

This small algorithm can be calibrated by the variables QueueLengthOfThreeVehicles and GreenTime. To fit this algorithm for a platoon of three vehicles.

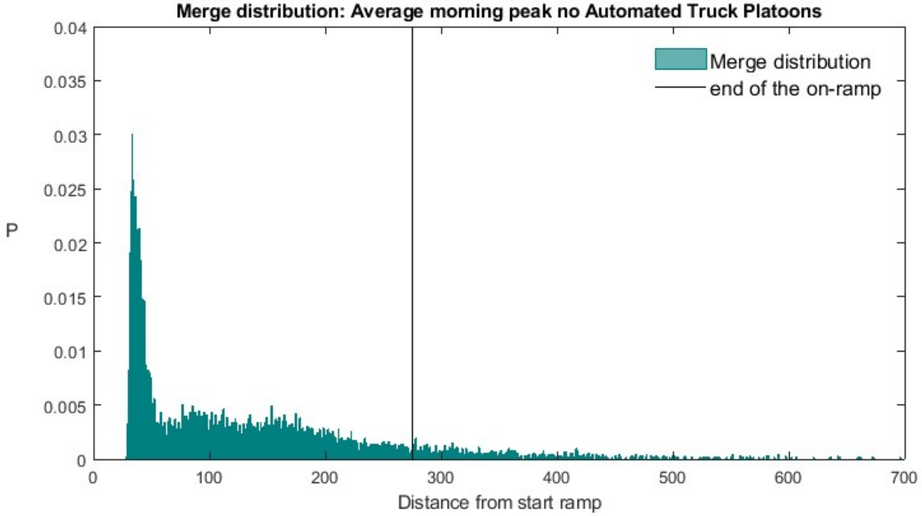
QueueLengthOfThreeVehicles = 30 meters

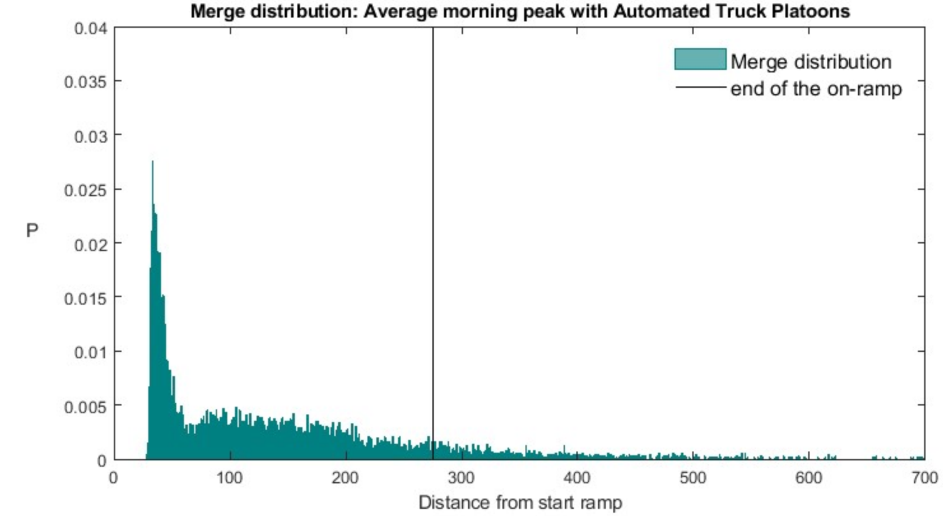
GreenTime = 6.0 seconds

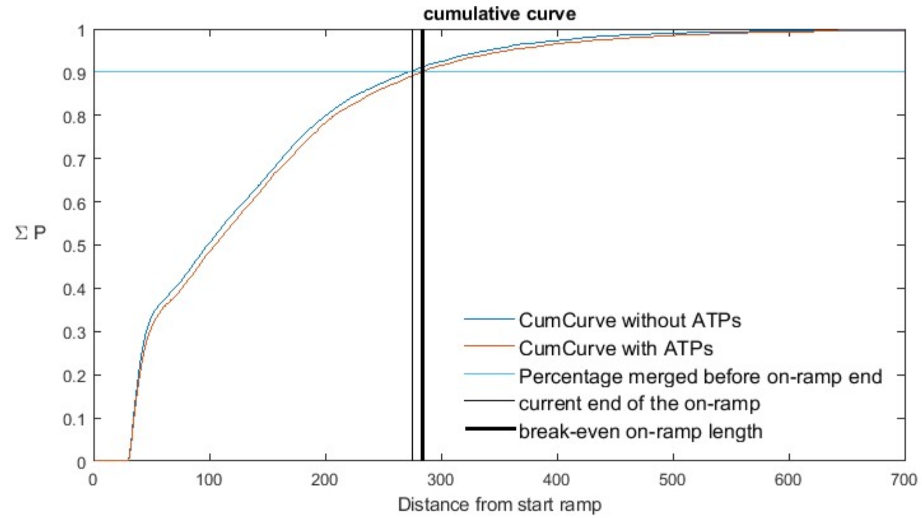
Appendix 3 Guide to implementing homogenous vehicles in VISSIM

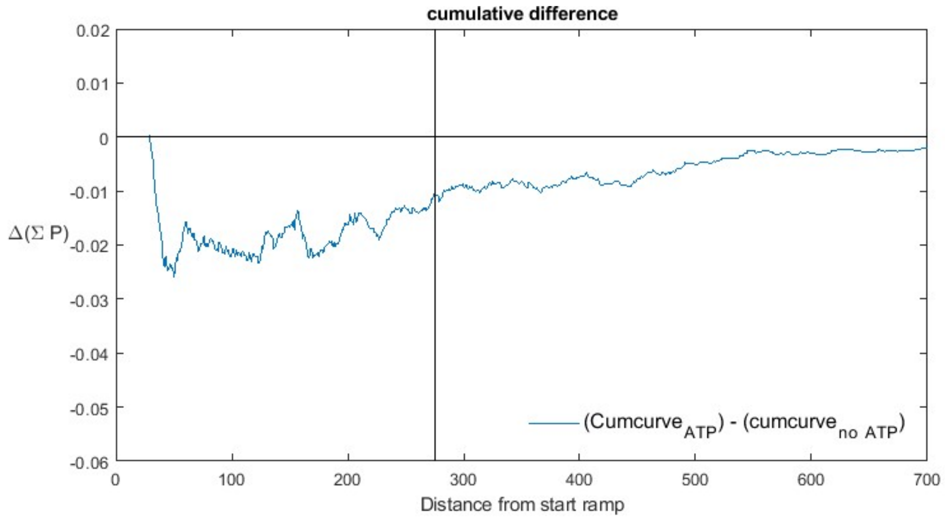
- Draw your network with a separate lane for TP spawns
- Create Functions:
    - Maximum acceleration (based on HGV)
        - Reduce the values all to the mean, so there is no variance
    - Maximum deceleration (based on HGV)
        - Reduce the values all to the mean, so there is no variance
- Create new distributions
    - Power → 500 without variance
    - Weight → 10 000 without variance
    - desired speed (if willing to use lane change warnings for early decoupling)
        - flat 360 km/h for left changing
        - flat 396 km/h for right changing
- Create a Vehicle type for Truckplatoons (21x)
    - Static:
        - Cat: HGV
        - VM: HGV
    - Func & dist
        - Max acceleration → newly created one
        - Des accel → HGV
        - Max decal → newly created one
        - Desired decal → HGV
        - Weight → newly created
        - Power → newly create d
    - External driver model
        - |V| use external driver model
        - Select the Drivermodel
        - No parameterfile needed
- Create a vehicle class containing your new vehicle type
- Create a vehicle composition that only contains your new vehicle type
    - DesSpeedDistr. 80 km/h
- Install the ramp metering system
    - See the install guide of the ramp meter
- Create a driving behaviour for right-side rule with decision on 0sec for TP
- Create a driving behaviour for rightside rule with decision on 10s for HGV
- Change the lane changing behaviour to right-side rule (slow lane rule) for TP and HGV on motorway (freelane selection).

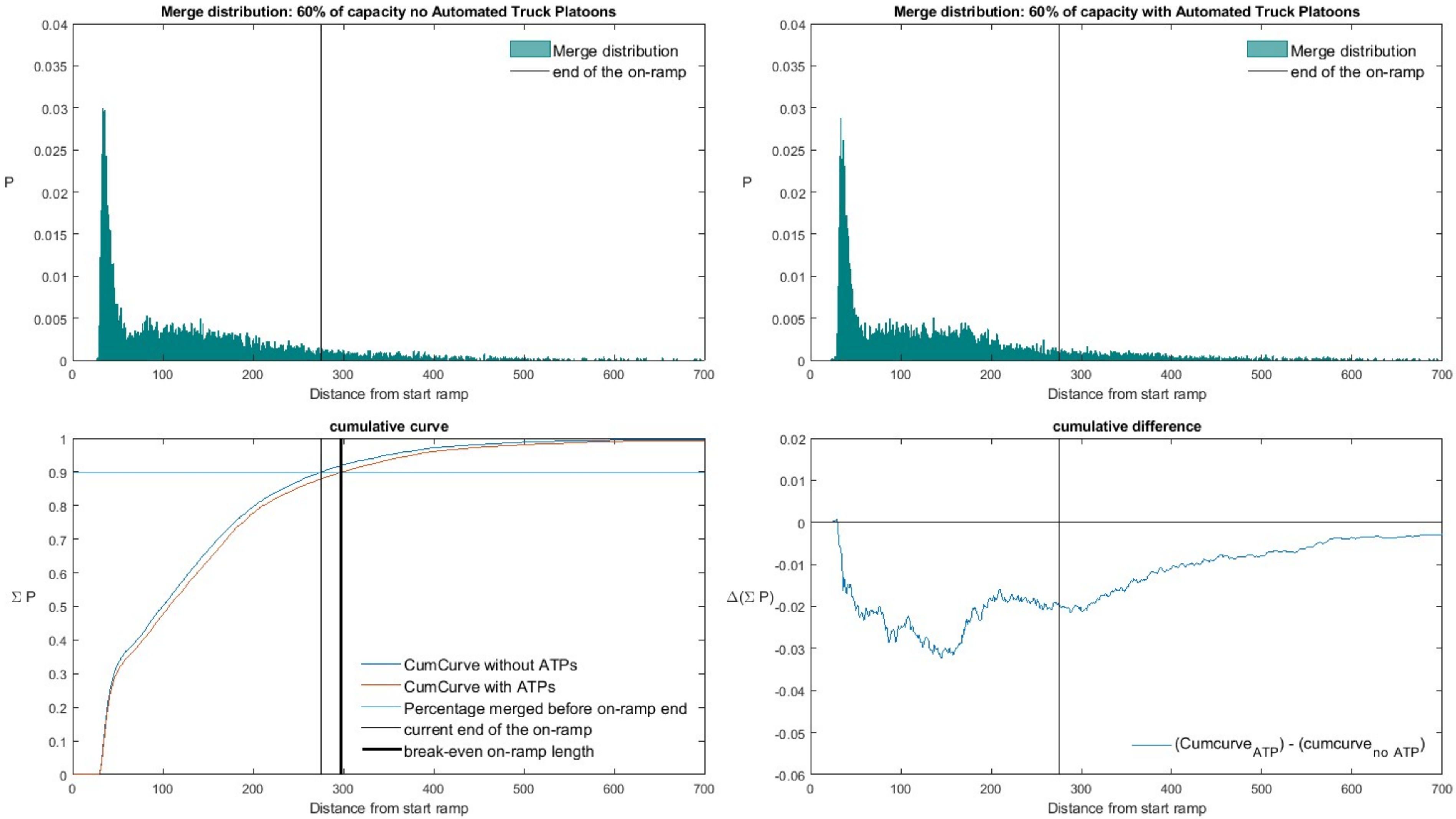
Appendix 4 Graphs of the results of ATPBON simulation: 10 runs

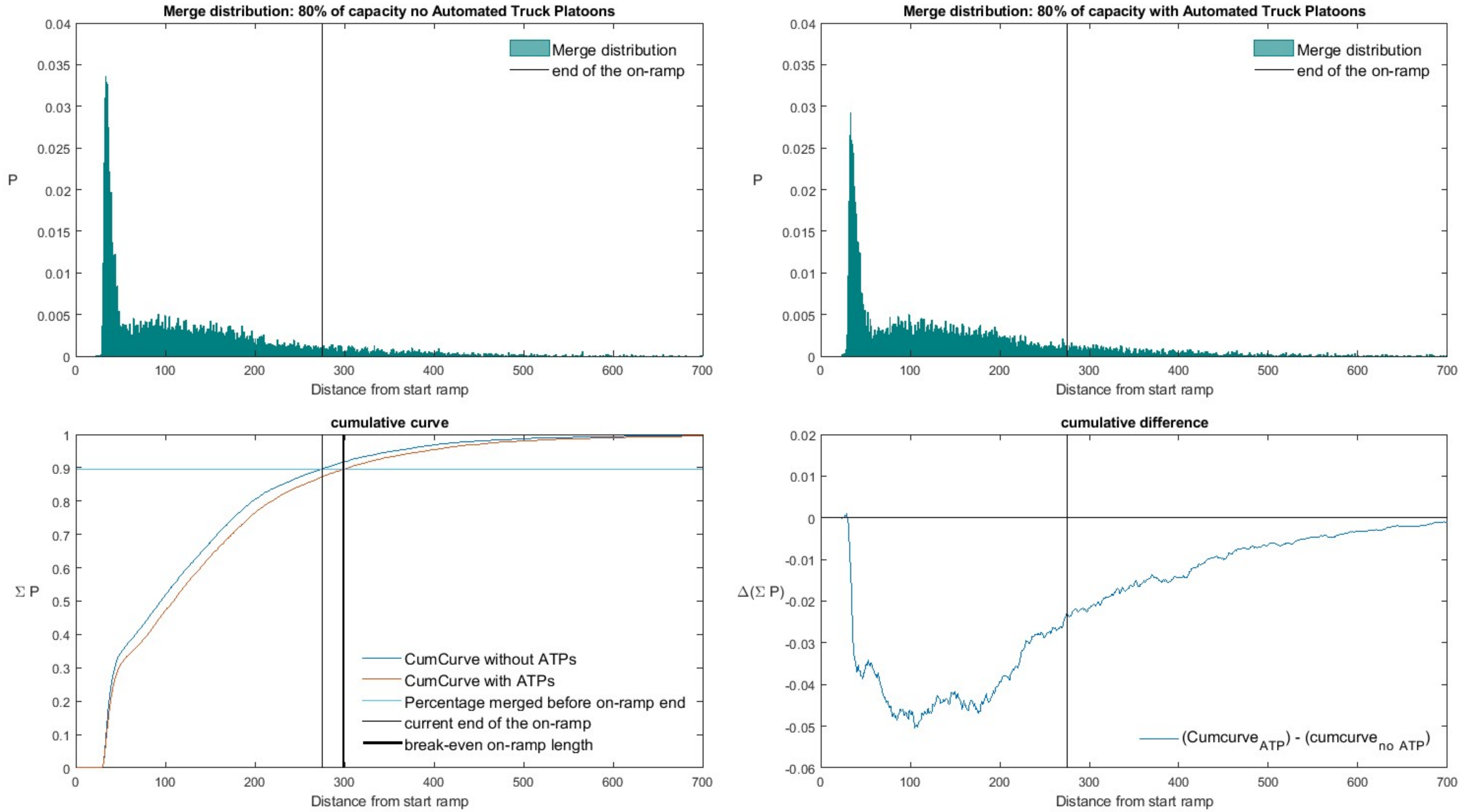




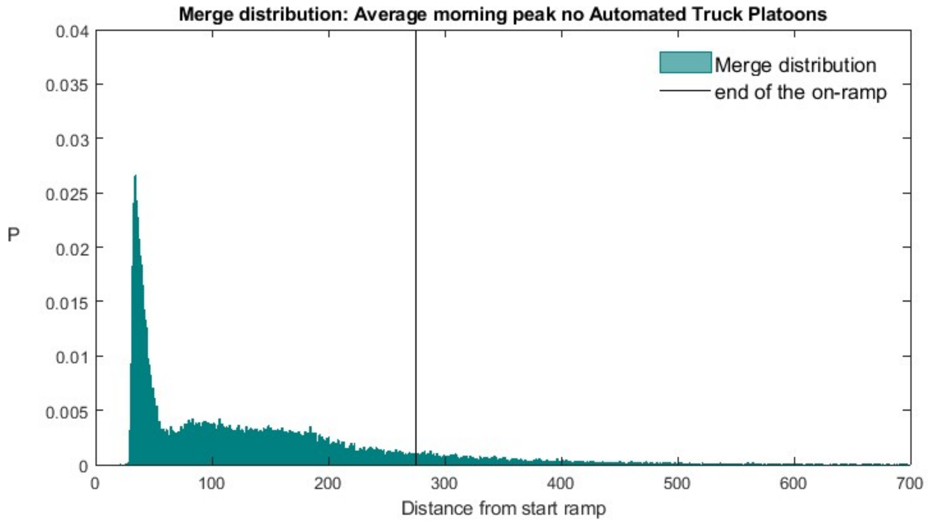


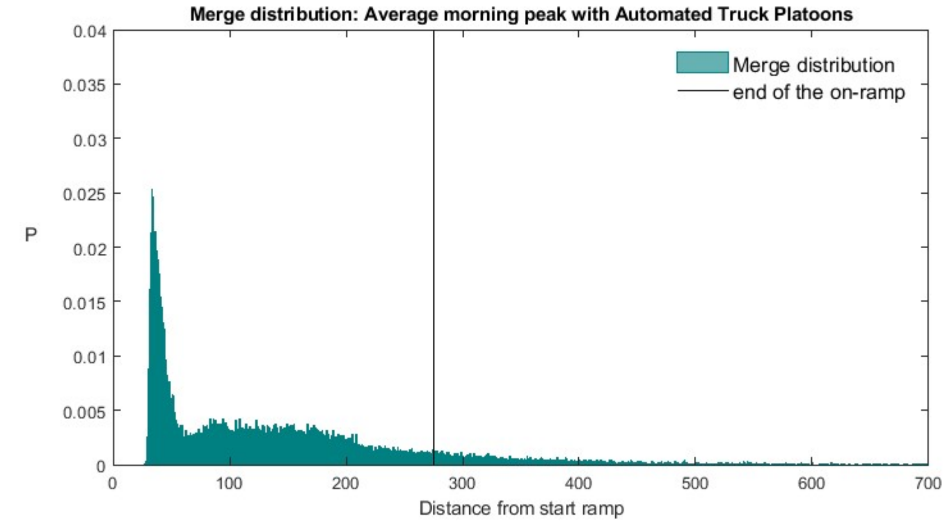


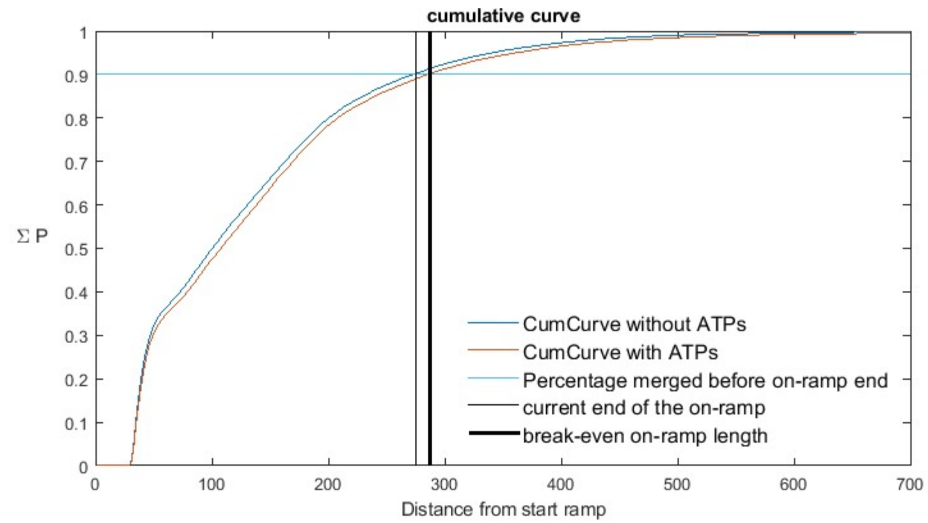

Merge distribution: 60% of capacity no Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
Merge distribution: 60% of capacity with Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
cumulative curve
Σ P
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before on-ramp end
current end of the on-ramp
break-even on-ramp length
Distance from start ramp
cumulative difference
Δ(Σ P)
(Cumcurve ATP) - (cumcurve no ATP)
Distance from start ramp

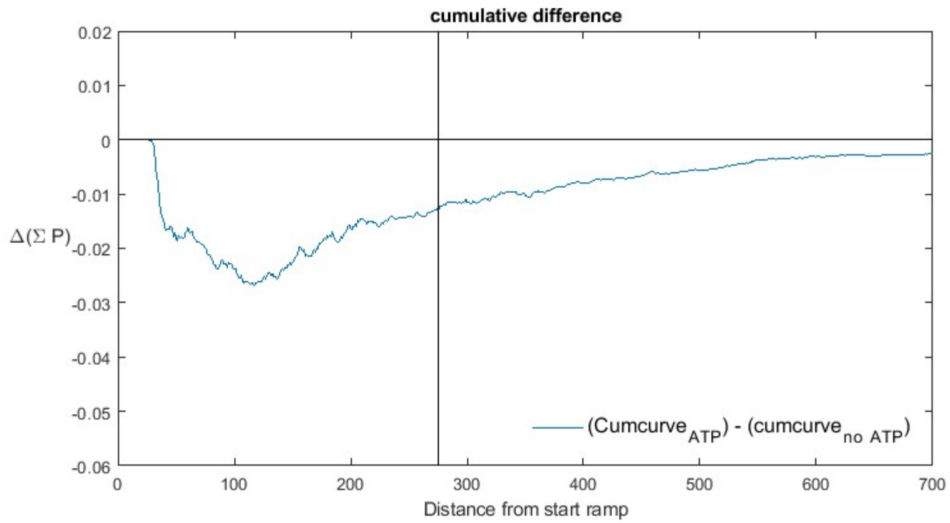

Merge distribution: 80% of capacity no Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
Merge distribution: 80% of capacity with Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
cumulative curve
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before on-ramp end
current end of the on-ramp
break-even on-ramp length
Σ P
Distance from start ramp
cumulative difference
(Cumcurve ATP) - (cumcurve no ATP)
Δ(Σ P)
Distance from start ramp

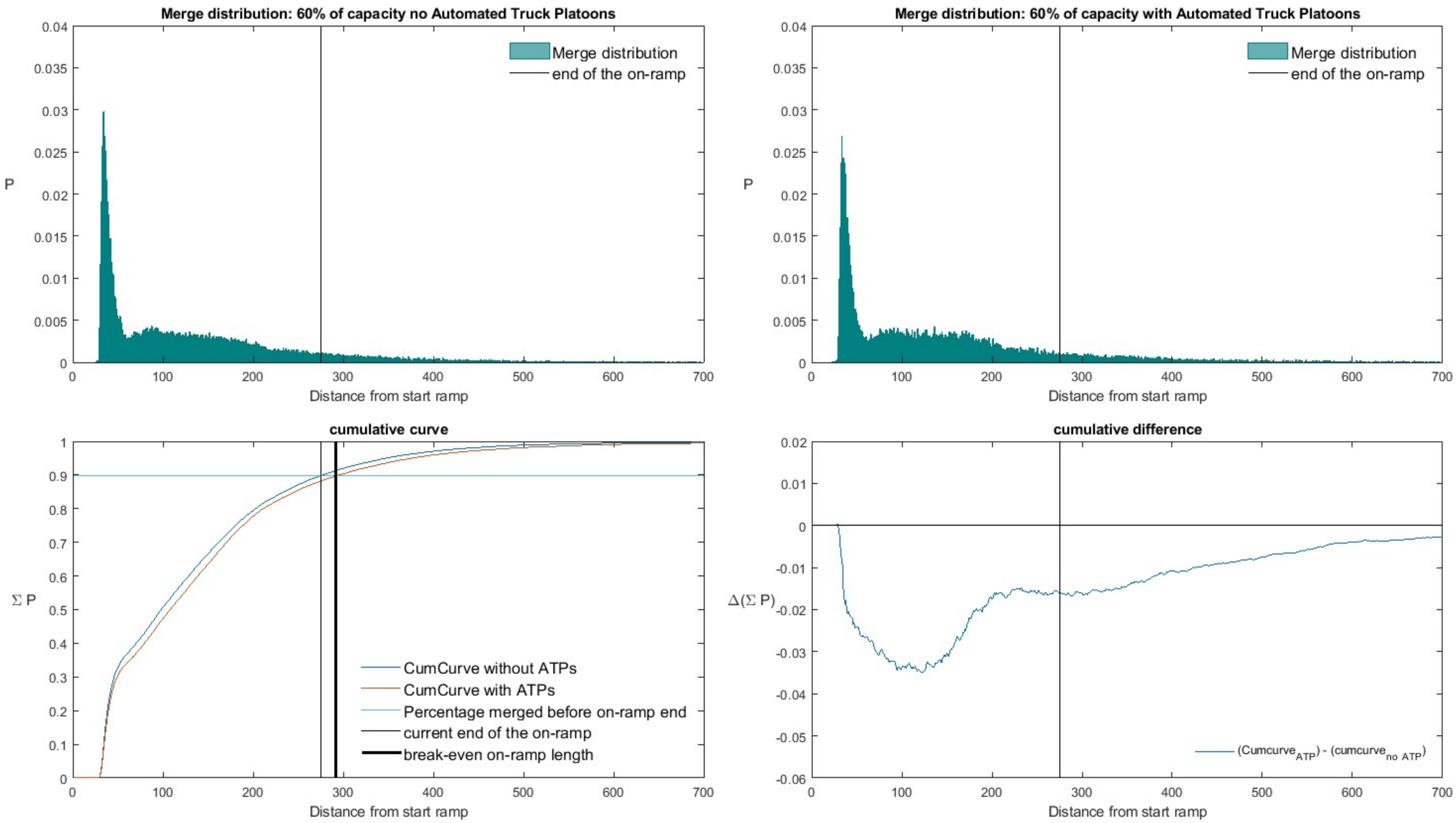
Appendix 5 Graphs of the results of ATPBON simulation: 50 runs



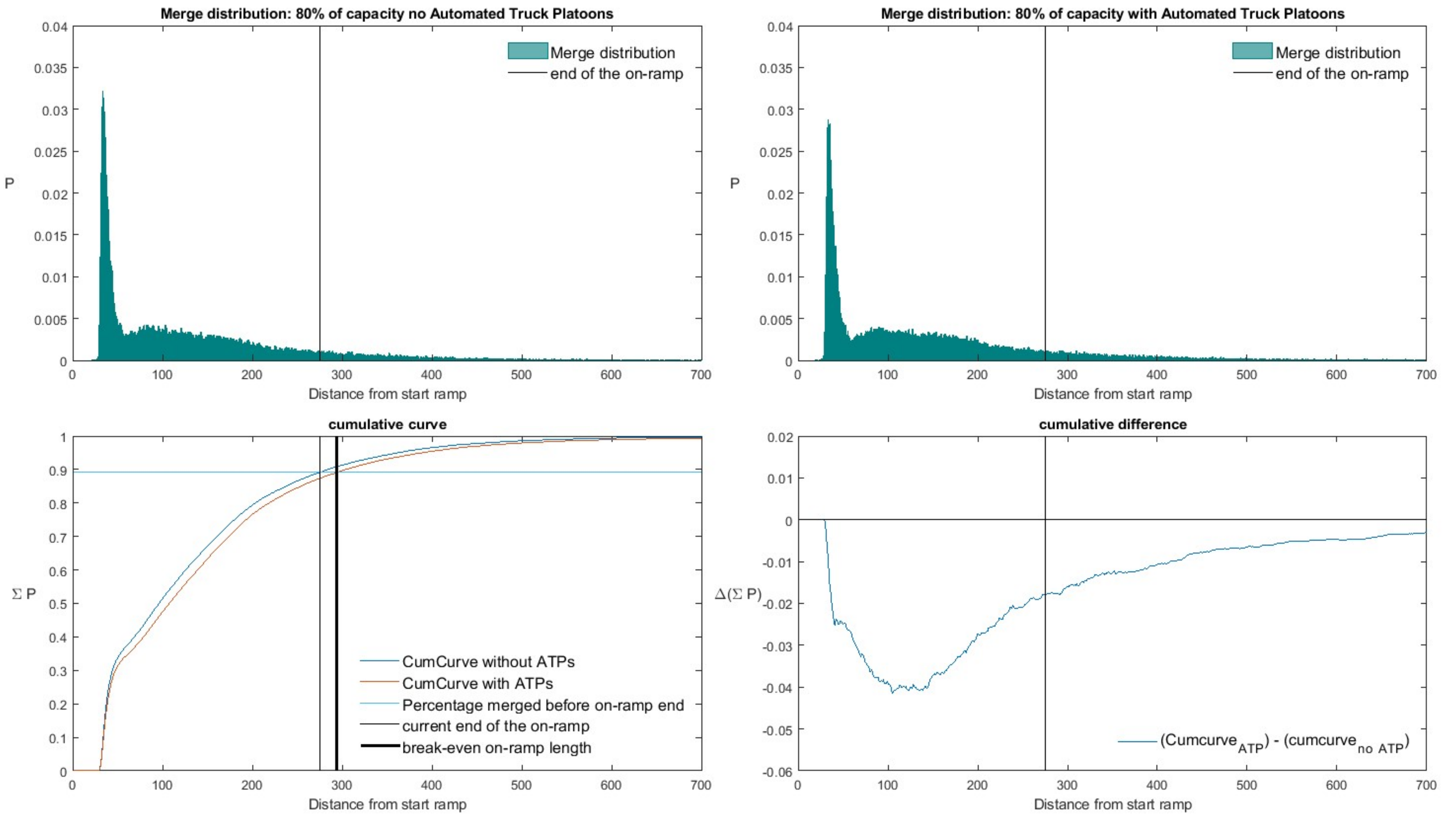




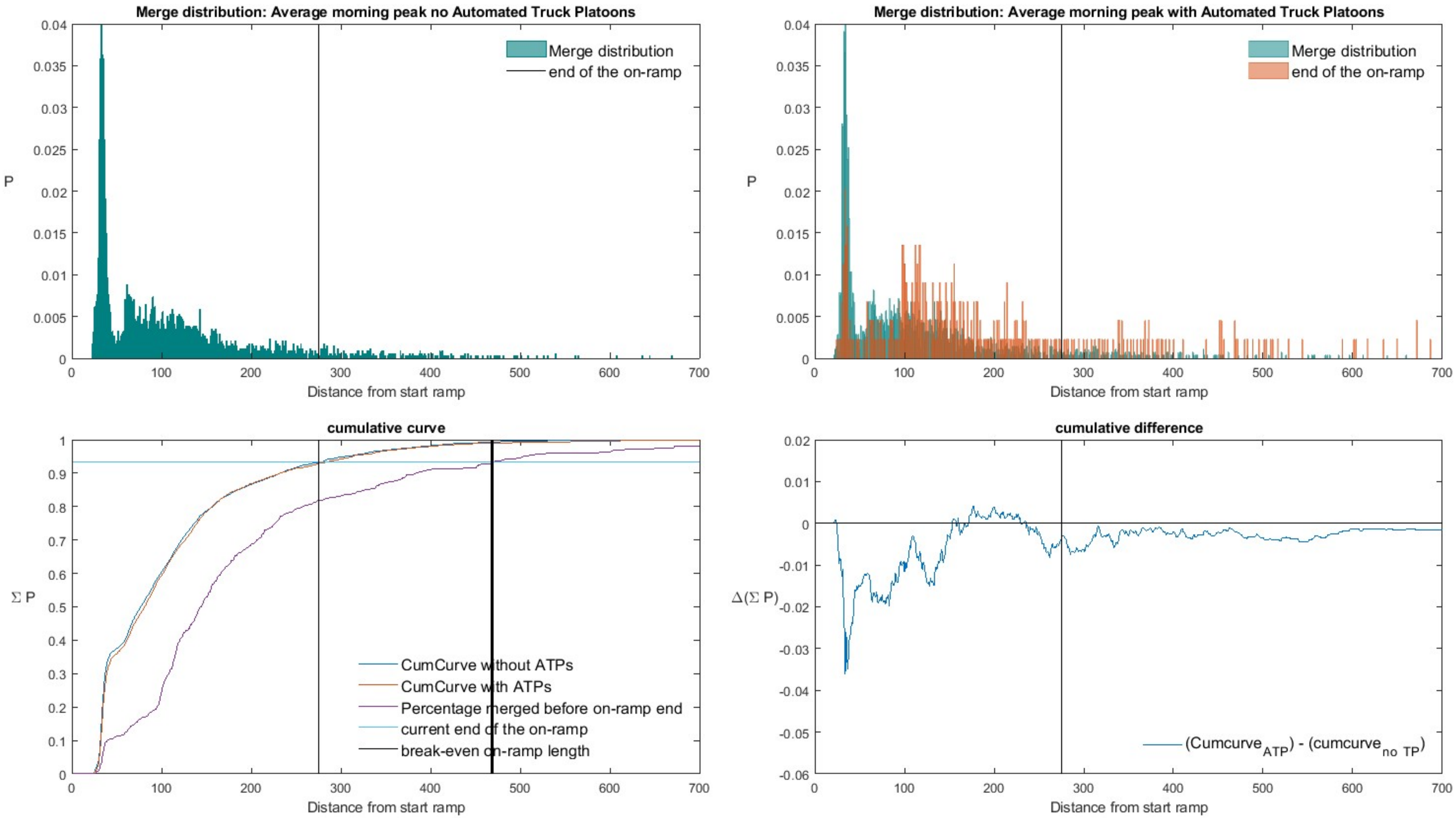


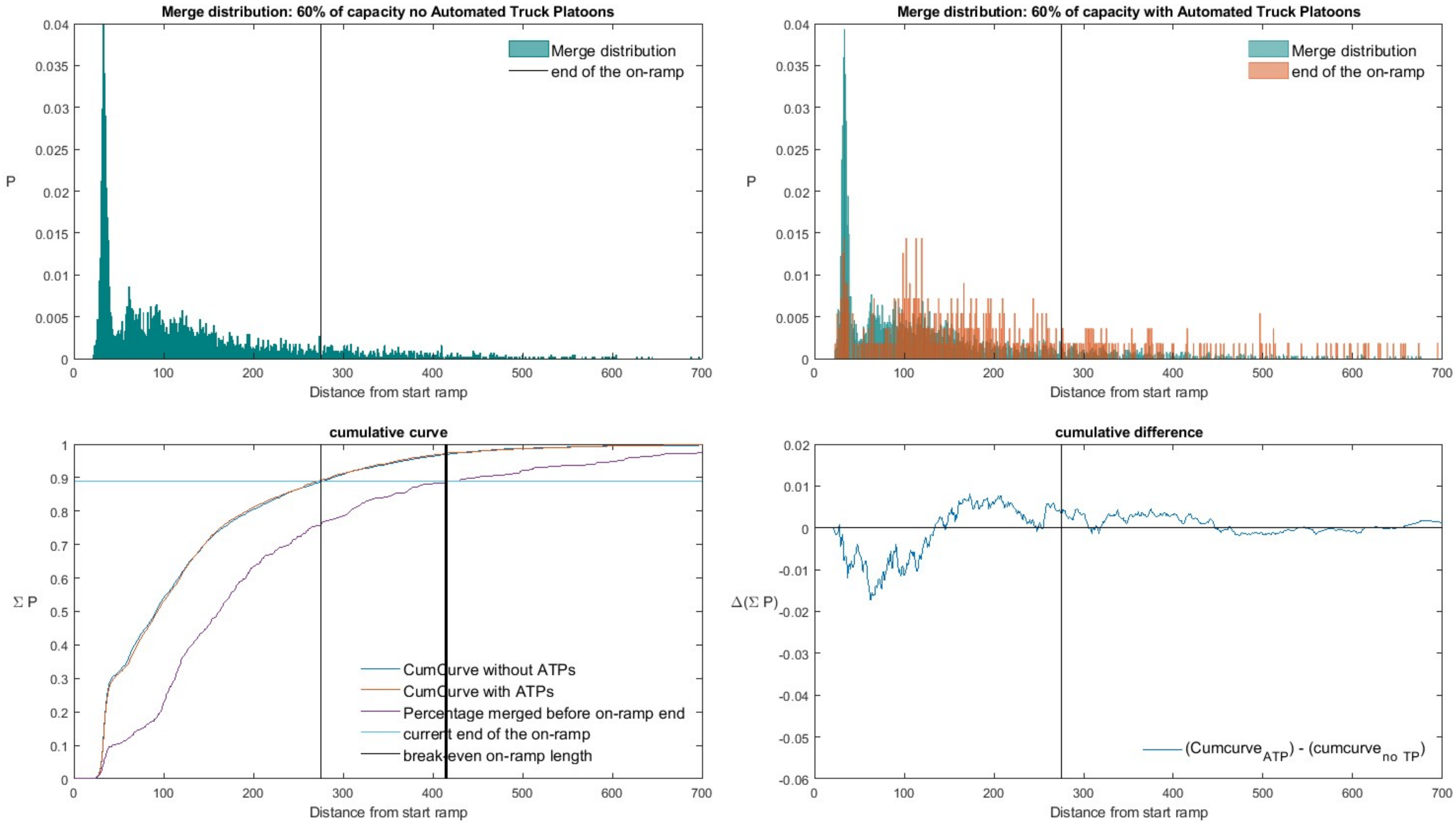


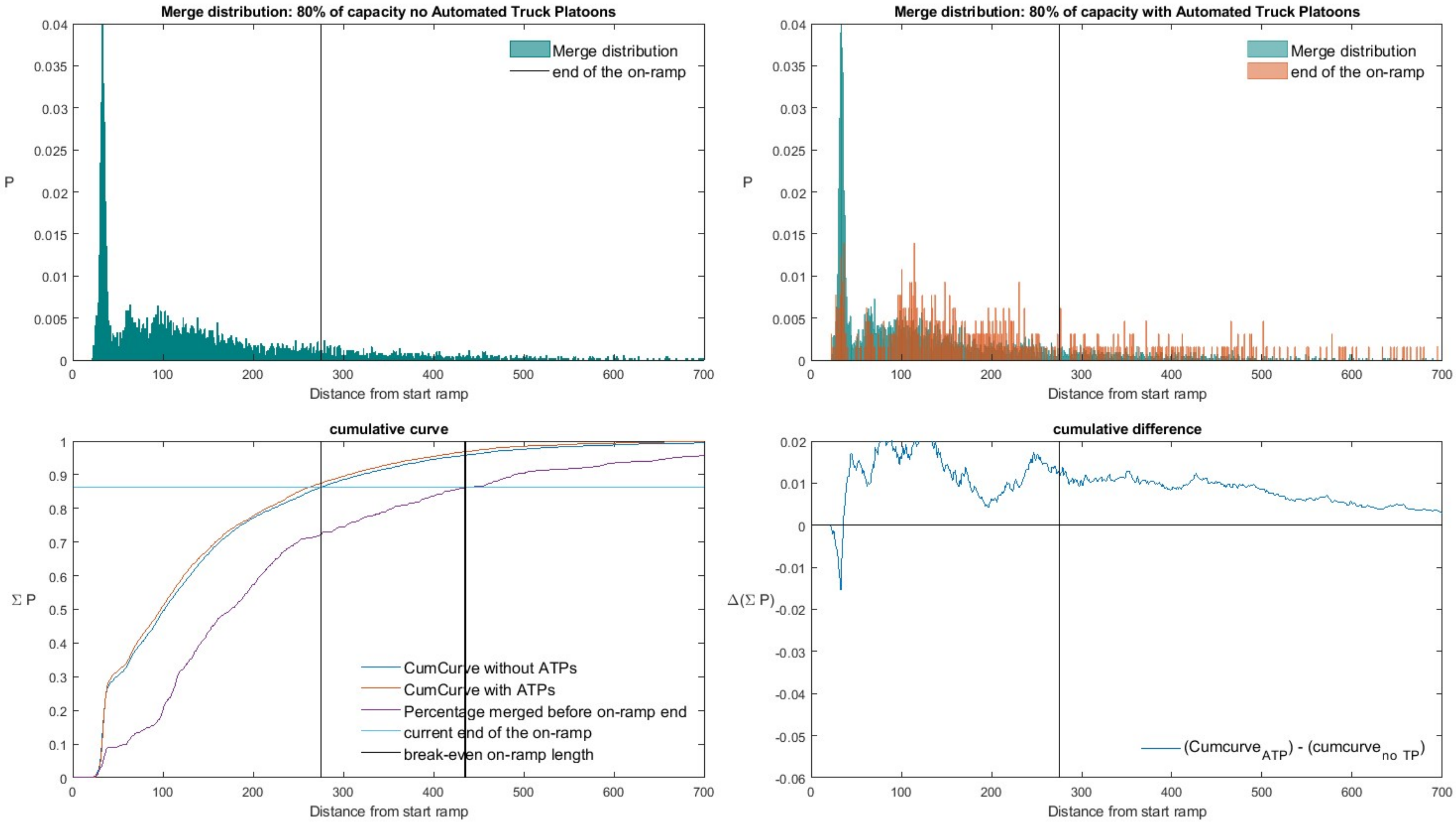
Merge distribution: 60% of capacity no Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
Merge distribution: 60% of capacity with Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
cumulative curve
Σ P
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before on-ramp end
current end of the on-ramp
break-even on-ramp length
Distance from start ramp
cumulative difference
Δ(Σ P)
(Cumcurve ATP) - (cumcurve no ATP)
Distance from start ramp


Merge distribution: 80% of capacity no Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
Merge distribution: 80% of capacity with Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
cumulative curve
Σ P
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before on-ramp end
current end of the on-ramp
break-even on-ramp length
Distance from start ramp
cumulative difference
Δ(Σ P)
(Cumcurve ATP) - (cumcurve no ATP)
Distance from start ramp

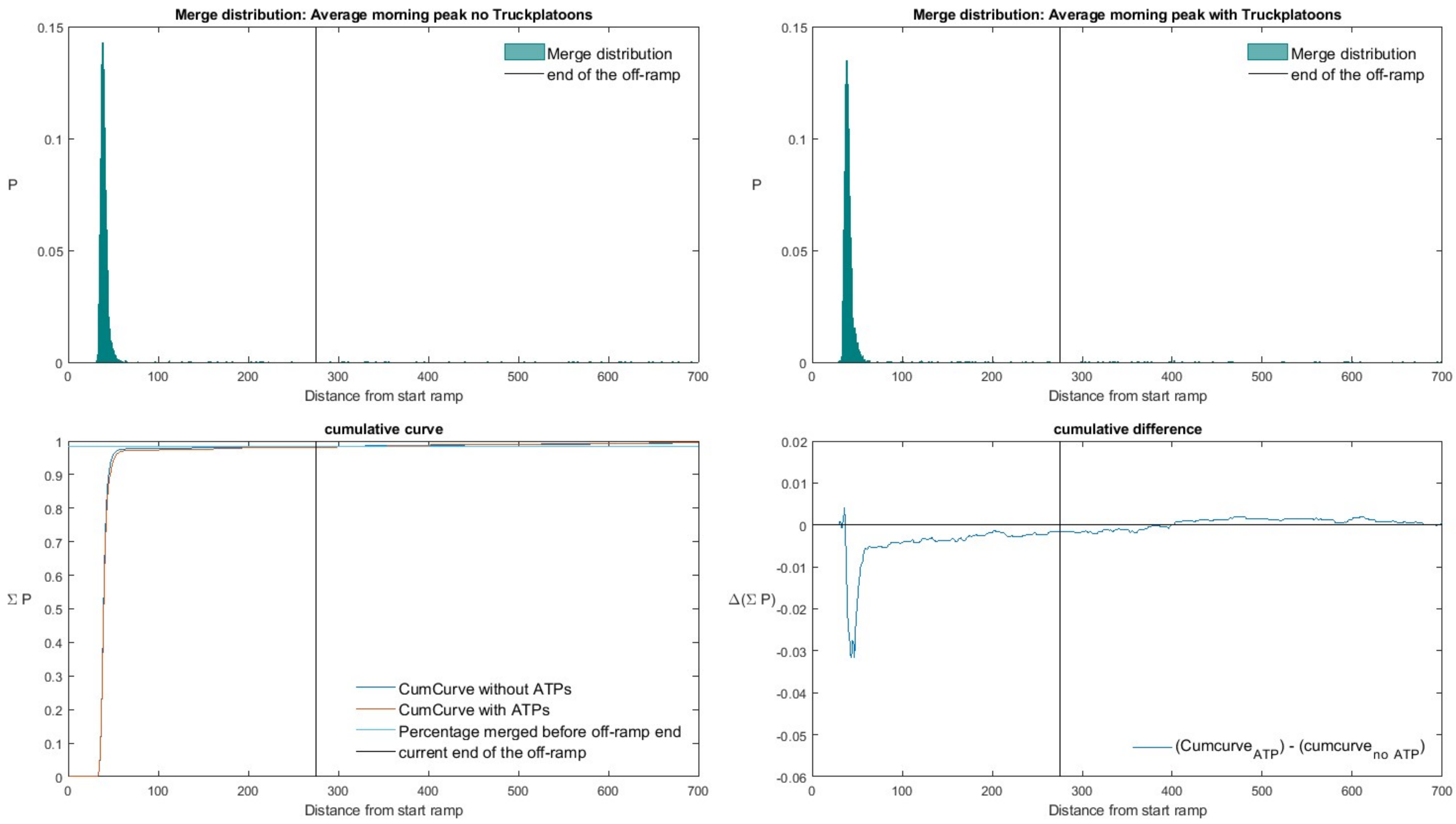
Appendix 6 Graphs of the results of ATPOON simulation: 10 runs

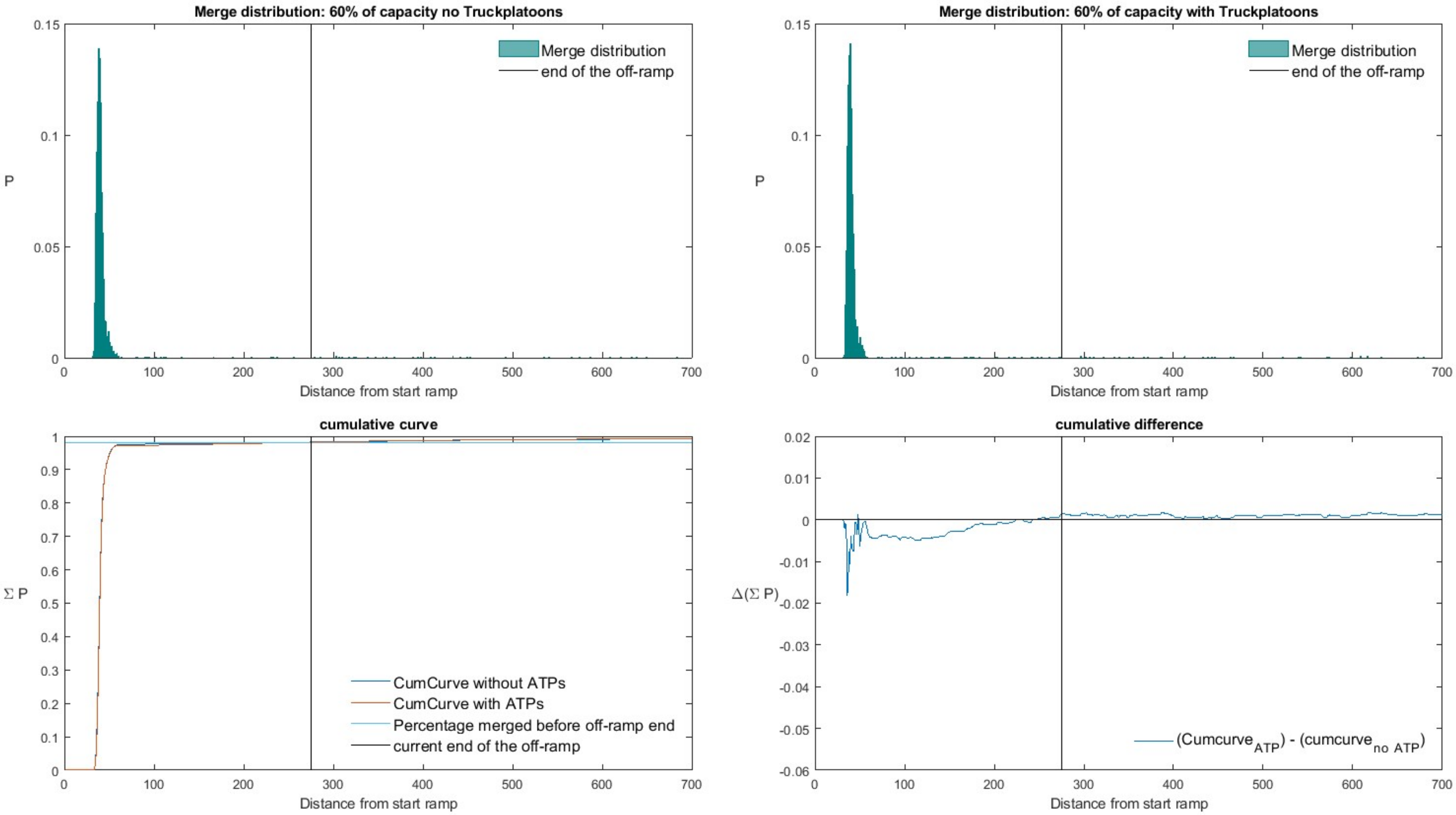


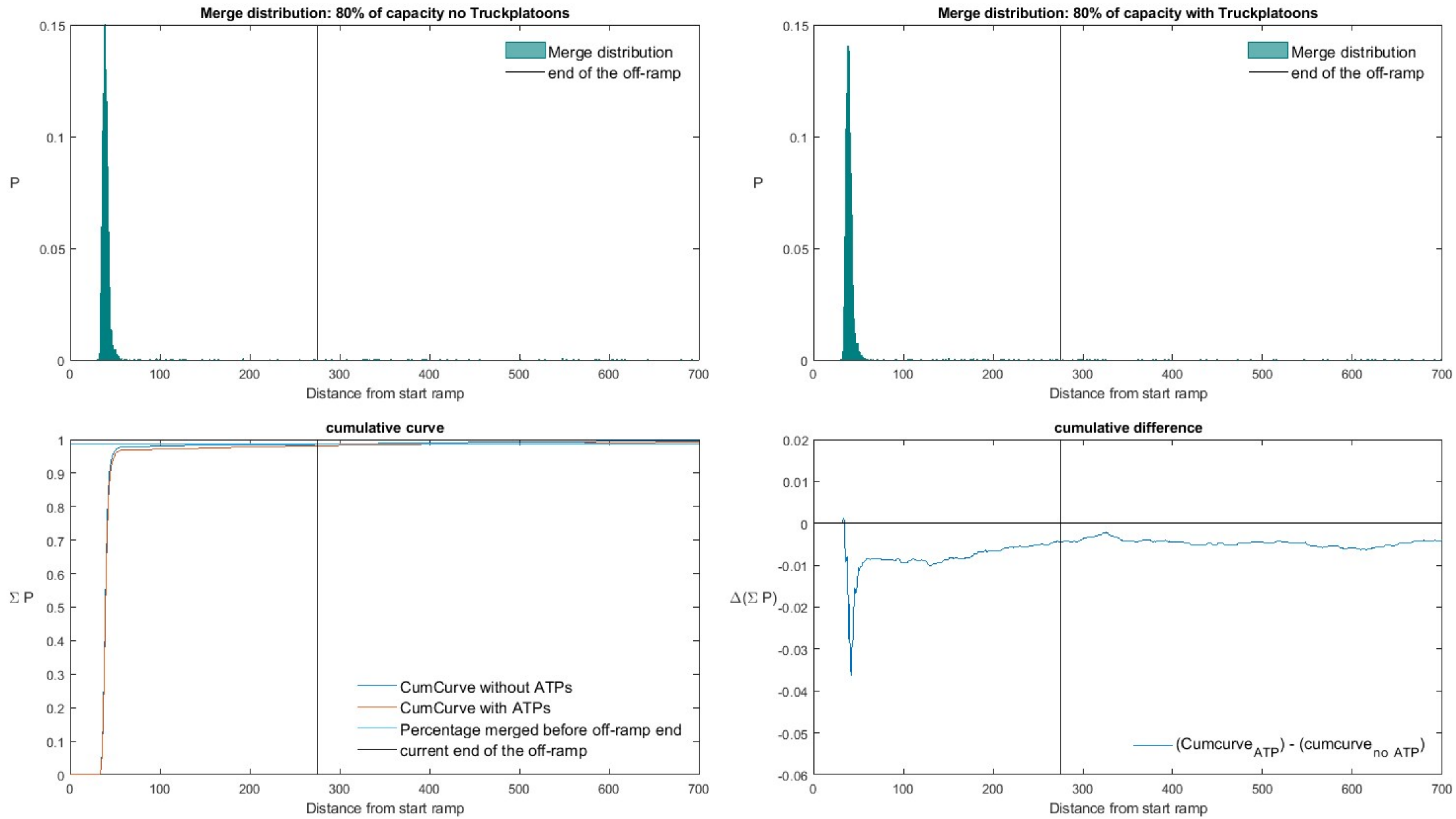

Merge distribution: 60% of capacity no Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
Merge distribution: 60% of capacity with Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
cumulative curve
ΣP
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before on-ramp end
current end of the on-ramp
break-even on-ramp length
Distance from start ramp
cumulative difference
Δ(Σ P)
(Cumcurve ATP) - (cumcurve no TP)
Distance from start ramp


Merge distribution: 80% of capacity no Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
Merge distribution: 80% of capacity with Automated Truck Platoons
Merge distribution
end of the on-ramp
P
Distance from start ramp
cumulative curve
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before on-ramp end
current end of the on-ramp
break-even on-ramp length
Σ P
Distance from start ramp
cumulative difference
(Cumcurve ATP) - (cumcurve no TP)
Δ(Σ P)
Distance from start ramp

Appendix 7 Graphs of the results of ATPBOFF simulation: 10 runs




Merge distribution: 60% of capacity no Truckplatoons
Merge distribution
end of the off-ramp
P
Distance from start ramp
Merge distribution: 60% of capacity with Truckplatoons
Merge distribution
end of the off-ramp
P
Distance from start ramp
cumulative curve
Σ P
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before off-ramp end
current end of the off-ramp
Distance from start ramp
cumulative difference
Δ(Σ P)
(Cumcurve ATP) - (cumcurve no ATP)
Distance from start ramp


Merge distribution: 80% of capacity no Truckplatoons
Merge distribution
end of the off-ramp
P
Distance from start ramp
Merge distribution: 80% of capacity with Truckplatoons
Merge distribution
end of the off-ramp
P
Distance from start ramp
cumulative curve
CumCurve without ATPs
CumCurve with ATPs
Percentage merged before off-ramp end
current end of the off-ramp
Σ P
Distance from start ramp
cumulative difference
Δ(Σ P)
(Cumcurve_ATP) - (cumcurve_no ATP)
Distance from start ramp