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Active platoon formation in congestion with Dynamic Dedicated Lane Sections (DDLSs)

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Preface

This thesis is the graduation work that concludes my Master of Science programme. The work has been conducted at ITS Edulab, which is a collaboration institute between Rijkswaterstaat (the Dutch road authority) and Delft University of Technology.

This research could not have been done without the help of many people, especially not without my supervisors. To start with dr. Meng Wang, who has been a source of information throughout my quest to develop a suitable platoon formation strategy. With his knowledge, patience and sense of humour, the meetings were constructive and never boring. Henk Taale, another daily supervisor, helped me to see the red line in my research. With his knowledge on day to day operations on the Dutch motorway the research kept its sense of reality, which eventually could help the actual implementation of the developed strategy. The kind attention to me and my questions, which included insightful thoughts on the graduation process, helped me to focus and relax at the same time. Furthermore, my gratitude goes out to the chairman of the committee, Bart van Arem. Also a very kind and knowledgeable man, that helped me to understand myself better (not chaotic but associative). At the same time his constructive criticism on the graduation work inspired me to keep improving and deliver the best result possible. Riender Happee, the supervisor from 3ME, paid attention to the other aspects of automated driving (e.g. safety, comfort). His eye for detail (deleted vehicles) started many discussions in the meetings that made my graduation work more complete.

Besides my committee I would like to thank Wouter Schakel, who helped me understand MOTUS, without his help this work would not have been possible. Also Lin Xiao was a huge help in developing my strategy in MOTUS, her feedback on MOTUS implementations and other ideas was indispensable. Last but certainly not least, I would like to thank my girlfriend Esmeralda. The everyday discussions about my thesis helped out a lot, but your unconditional support got me through the entire graduation process.

With this research new platoon formation strategies are developed. These strategies increase the platoon formation efficiency when the initial deployment of the connected and automated vehicles (CAVs) takes place. Hopefully this research will contribute to a future with automated vehicles, where I do not have to touch the steering wheel anymore.

Aiko Dokter

Delft, September 2018

Summary

In order to find a solution for congestion many studies research and implement automated driving (AD). This research considers connected and automated vehicles (CAVs) as a prime candidate for this solution. CAVs are able to drive in platoons with small inter-vehicle time gaps. In this research the CAV is a cooperative adaptive cruise control vehicle that adopts an inter-vehicle fixed time gap of 0.7 seconds, this is calculated by Ploeg et al. (2014) to be feasible for real-world implementation. CAV platoons with these small inter-vehicle time gaps can increase the throughput on the motorway, however before this will occur a high penetration rate is deemed necessary (van Arem et al., 2006). This research is meant to look at the implementation of CAVs when the penetration rate is still low, this is the case at initial deployment.

The problem with CAVs platooning on the motorway with a low penetration rate, is that the actual formation of platoons is hard to achieve due to mixed traffic conditions. Mixed traffic conditions are conditions that have "normal" (human driven) vehicles and CAVs present on the motorway network. In these conditions the conventional vehicles block the CAVs and prohibit them to form platoons on the motorway. On the other hand the congested conditions prohibit the CAVs to form platoons alongside the motorway. This would require the CAVs to merge back onto the motorway, which would increase the congestion (Mathijssen, 1989). Therefore, the objective that this research tries to obtain, is stated as:

"Develop platoon formation strategies that allow the CAVs to form platoons on the motorway in mixed and congested traffic, without deteriorating the traffic conditions."

Along with this objective, an increase in capacity drop is to be avoided and the traffic congestion should not get worse. This means that the outflow after the bottleneck should remain the same and the total time spent in the network (TTSiS) should not increase. To test whether or nto these objectives are obtained the research was build up out of two elements: *1.* developing a new strategy and *2.* performing simulation experiments to test the effects the developed strategies have on the traffic conditions. In order to develop a platoon formation strategy, the state of the art knowledge on: CAV platoon formation, traffic management solutions, traffic jam characteristics and microscopic traffic simulators is researched.

The literature study

The literature study is structured according to the hierarchical control layers as described by Shladover (2005). In this structure there are five layers: The network layer, the link layer, the coordination layer, the regulation layer and the physical layer. In three of those layers the subjects of *"CAVs"* and *"Platooning"* reside. The explanation of the capabilities of a CAV reside in the regulation layer, the active platoon formation strategy resides in one or even two levels higher, the coordination and link layer level. In the latter two levels an active platoon formation strategy is developed.

The research nor the development of the CAV capabilities within the regulation layer falls within the scope of this research. It needs to be explained because without the individual CAV operations there would be no platooning with small inter-vehicle time gaps. Below (in equation 1) the multi-anticipative controller with a collision avoidance function (Van Maarseveen, 2017; Wang, 2014) as is implemented in this research is given, this describes the following behaviour of the CAV:

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

With:

$a_{i,t}^{car-following}$: the desired acceleration of the CAV.
$(s_{i,t} - s_{i,des,t})$: the delta between the *actual gap* and *desired gap* towards the predecessor.
$R(s)$: a collision avoidance function described by Mullakkal-Babu et al. (2016).
$(v_{i-1,t} - v_{i,t})$: the difference in speed in comparison with the predecessor.
$a_{i-1,t}$: the passed on acceleration of the predecessor by the means of communication (CAV).
k_s, $k_{\Delta v}$ and k_a are parameters (see appendix B).

The CAV behaviour of the leader is described by an adaptive cruise control (ACC) controller. This will subtract $k_a a_{i-1,t}$ from equation 1, because it becomes zero since there is no communication between a conventional vehicle and the CAV. When a predecessor is out of range the controller of the leader will reduce to cruise control (CC).

Although the regulation layer provided the description of the CAV control algorithm, the development of the platoon formation strategies takes place in the coordination and link layers and this is the focus of the literature research. The coordination layer ensures the vehicle trajectory and "manoeuvres are coordinated among adjacent vehicles" (Shladover et al., 2012). The link layer shifts it focus towards managing traffic flows.

In literature two types of platoon formation strategies residing in the coordination layer are found, *passive platoon formations* and *active platoon formations*. With passive platoon formation the platoon formation relies solely on the CAVs via vehicle to vehicle (V2V) communication. With active platoon formation the vehicle interacts with the infrastructure (V2I communication) to form platoons. None of the existing platoon formation strategies showed that they were able to form platoons on the motorway, in congestion and in mixed traffic. Presenting the research gap: *"There is no platoon formation strategy that can form platoons on the motorway, in congestion and in mixed traffic."*.

Literature topics that reside in the link layer mainly concern traffic flow management solutions. The solution direction that appeared was the use of dynamic dedicated lanes. In these lanes the CAVs might be able to come together and form platoons, even though they are stuck in a traffic jam. Because the strategy has to take place in congestion, advantageous characteristics of a traffic jam were investigated. A fixed bottleneck, low safe speeds and a the high amount of vehicles per kilometre (density) could assist with CAV platoon formation. Also, a suitable simulation model in which the strategies can be developed was also found, i.e. MOTUS. It stands for: microscopic open traffic simulation and is based on the LMRS and IDM+ models by Schakel et al. (2012); Kesting et al. (2010).

Two platoon formation strategies

With the method of prototyping two platoon formation strategies have been developed, both strategies are based on the same foundation. The two different platoon formation strategies are: "an activation strategy with an one-time density threshold check" and "an activation strategy with a permanent density threshold check". The platoon formation strategies apply dynamic dedicated lane sections (DDLSs) (figure 1, area no. 5) in order to let CAVs platoon on the road in congested and mixed traffic conditions.

The platoon formation occurs on the network as described below in figure 1. The layout has five network sections; *(1.)* The designated jam area; *(2.)* The bottleneck; *(3.)* The inflow section; *(4.)* The outflow section and; *(5.)* The DDLSs area.

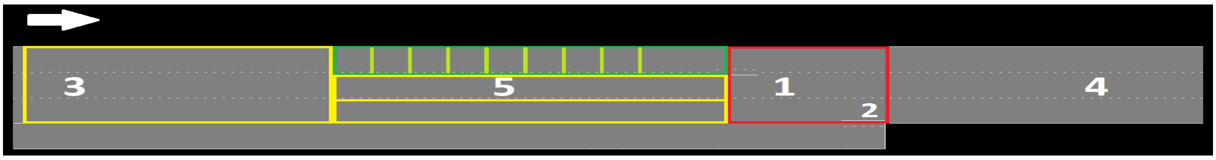

Figure 1. – The network layout, each sections has a different function.

Sections *2, 3, 4 and 5* are self-explanatory. The entire designated jam area (*(1.)*) should contain a traffic jam in order for the strategy to commence, this is to prevent a capacity drop.

The first, most downstream, DDLS becomes active if the density [vehicles/km] on that lane section passes the threshold of 41 vehicles per kilometre, once activated the lane section is dedicated to CAVs only. Once the threshold density of the next upstream section is reached (also 41 vehicles per kilometre) it also becomes dedicated. This process is shown in figure 2, row C and D.

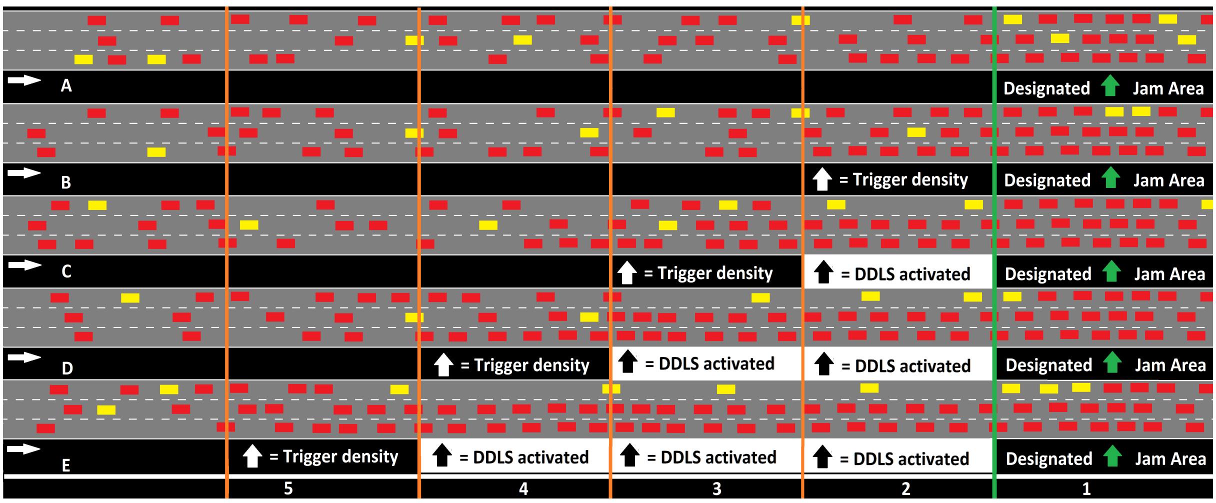

Figure 2. – Start of DDLS activation strategy, red vehicles are non-CAVs, yellow vehicles are CAVs. Motorways A to E are the same motorway at a next moment in time.

This dedication is deactivated once the same threshold is reached on the last, most upstream, DDLS. The deactivation process is the reverse of the activation process, as seen in figure 3.

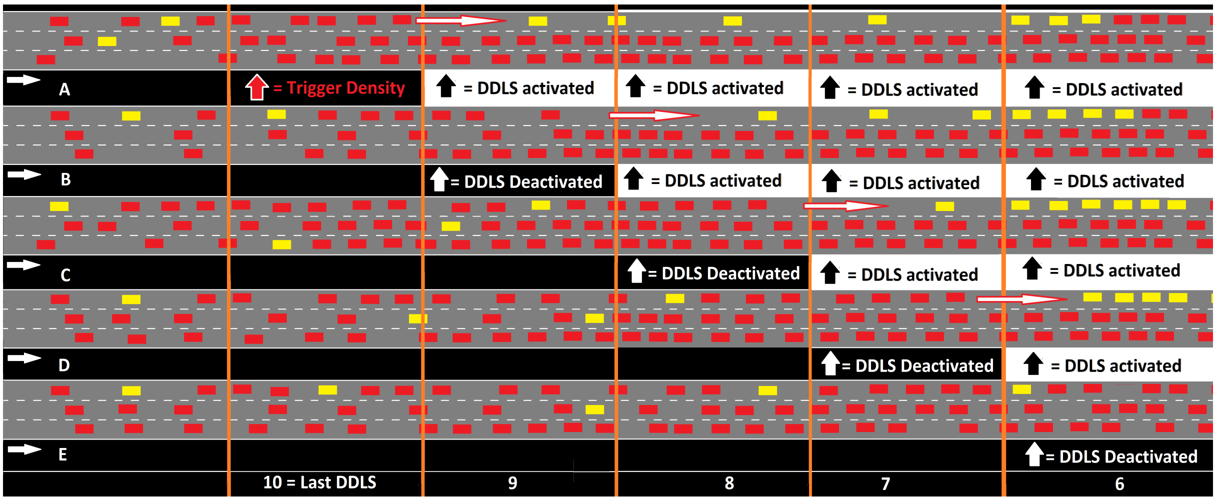

Figure 3. – End of the strategy, red vehicles are non-CAVs, yellow vehicles are CAVs. Motorways A to E are the same motorway at a next moment in time.

Both sections differ in the matter of the activation threshold, this is different considering its permanency. The lane sections in the strategy with an one-time density threshold check will remain activated once the density threshold has been reached in the first DDLS. The lane sections in the strategy with a permanent density threshold check, can deactivate before the last DDLS has been reached. This occurs once the density of a lane section has dropped below 35 vehicles per kilometre. Hence the name, the density is constantly (permanently) checked and if it drops below the threshold, the dedication for the considered section and the section upstream deactivates. In practice this means both platoon formation strategies deviate a lot.

An example of both strategies is shown in appendix F, these are images from the implemented strategies in MOTUS. Two videos of the strategies are on-line:
https://youtu.be/UMvCAn4Oxvc and https://youtu.be/i3-B-04_vHg. These are YouTube videos (Hurley et al., 2018)).

Simulation experiment set-up

To test the effects of the developed strategies a simulation experiment with different scenarios was created. In this experiment three types of variables are determined: the independent variables, the control variables and the dependant variables also known as the key performance indicators (KPIs). All variables used for the experiment are elaborated below.

The independent variables

The independent variables describe the variables that are varied. The strategies are varied between the two different strategies (mentioned above) and a control ("no") strategy. The other set of variables are the CAV penetration levels, i.e. the percentage of CAVs driving on the motorway. The different penetration levels are: 0%, 2%, 5%, 10%, 20%, 30% and 40%. This meant there were 21 different scenarios.

The control variables
The control variables determined the variables that did not change. These variables were determined by preliminary tests (see appendix D, they consisted of the following elements. *(1.)* The physical network as described by figure 1. *(2.)* The trigger density of the DDLS activation, as mentioned before, set at 41 vehicles per kilometre (for the "on" and "off" switch). *(3.)* A fixed demand pattern that resembles typical Dutch motorway conditions.

The dependent variables (the KPIs)
In order to show the feasibility of each strategy, five KPIs are presented. They represent traffic characteristics that are affected by the each strategy and the other independent variable, the CAV penetration rate. These variables indicate the effects the different scenarios have on the traffic conditions and platoon formation capabilities.

The five KPIs that were used are: *1.* An average platoon size indicator, *2.* the outflow (out of the traffic jam), *3.* The total time spent in the system (TTSiS), *4.* The DDLSs active time and *5.* the amount of deleted vehicles. The latter indicated whether or not a vehicle could merge and at the same time this was an indication of validity and safety.

Validation
The simulation results were validated by the elements that build up the simulation model (if these are invalid, the model itself is invalid). The elements that are validated (by their corresponding research) were the IDM+ and LMRS models of MOTUS (Kesting et al., 2010; Schakel et al., 2012) and the implemented CACC controller (Van Maarseveen, 2017). Moreover, the fundamental traffic characteristics of the control strategy were validated by a comparison to empirical evidence on motorway traffic. The characteristics that were validated were: the flow contour plots, the fundamental diagrams, the capacity drop and the shockwave propagation speed.

Thus, there are three strategy scenarios and seven CAV penetration rate scenarios, for a total of 21 scenarios. These scenarios were tested on their effect on the KPIs. The results determine whether or not the objectives of the research were met.

Simulation results and discussion

In the report all of the results are presented per KPI, in this executive summary the results are presented according to three key questions. The answer of the questions determine whether or not the objective is obtained.

Do the strategies work as intended?
The strategies work as intended this can be seen when comparing the flow contour plots with the "switch-on" detection plot (figure 4).

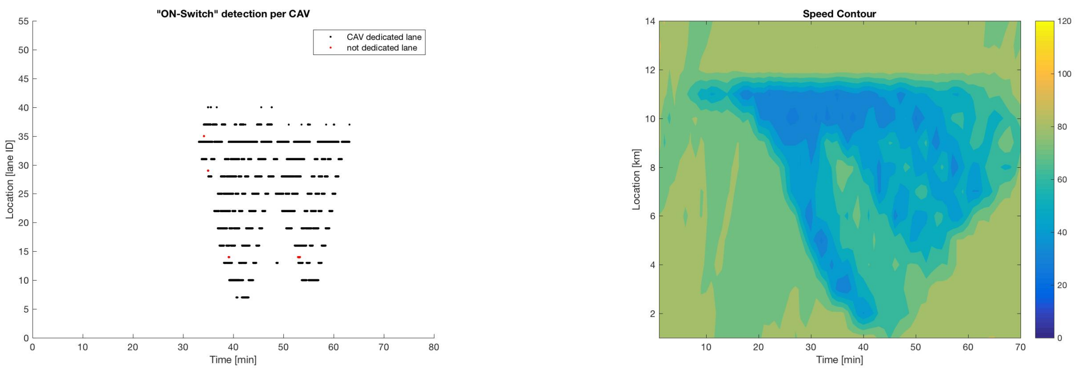

Figure 4. – The "on-switch" detection plot (left) compared to the speed contour (right), for the strategy with a permanent density threshold check and with 2% CAVs. Both describe location and time.

The following observations on the operations of the strategies can be made: *(1.)* the strategy turns "on" when a traffic jam occurs at the downstream DDLS, *(2.)* the strategy turns "off" when the traffic jam reaches the final DDLS (most upstream DDLS), *(3.)* the strategy turns of gradually (as intended, see figure 3), *(4.)* the different behaviour of the platoon formation strategy with a permanent density threshold check is present. The latter observation is shown by the bottom of the on-switch detection plot, it is turned of as soon as the density drops (below 35 vehicles per hour). The behaviour is seen with the strategy with an one-time density threshold check. Furthermore, *(5.)* the outflow did not present a capacity drop, this means that the designated jam area performs accordingly.

Are platoons actively formed, more effectively than with the control strategy?
The platoon formation strategies work as intended, therefore only the indication of the average platoon sizes remains to determines whether or not the first part of the objective is reached; Develop an active platoon formation strategy for CAVs to platoon "on" the motorway in congestion and mixed traffic. Figure 5 clearly indicates that the strategies actively forms platoons more efficiently than with the control ("no") strategy.

Are there any disadvantages?
The results already indicated that there was no increase in capacity drop. The increase of TTSiS would be a disadvantage and is an indication of the deterioration of traffic conditions, this means that the traffic jam would be worse than with the control strategy. Therefore the KPI of the TTSiS will complete the second part of the objective; (can platoon formation strategies be developed) **without the deterioration of the traffic conditions**. The **total** time spent in the system gives a result that is too positive, since it also accounts for the TSiS during the free flow conditions (about 2/3 of the time). Therefore a slightly adjusted KPI is used, namely TSiS, as seen in figure 6. This is the time spent in the system per individual vehicle. *Here the disadvantage appears; On average in congested conditions the TSiS for a non-CAV is 200 seconds more than for a CAV.* This disadvantage has to be mitigated (recommendations).

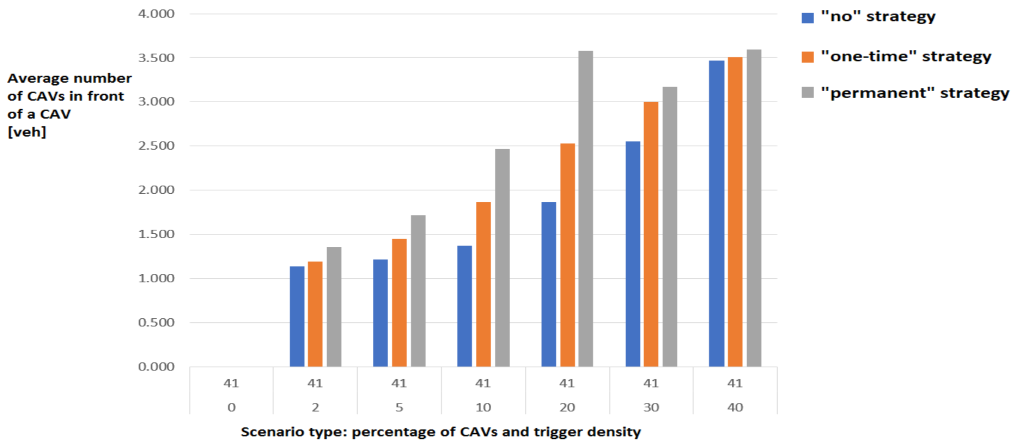

Figure 5. – An indication of average platoon size, with the weighed average (size of platoon over number of platoons) amount of CAVs directly preceding a particular CAV per penetration level scenario.

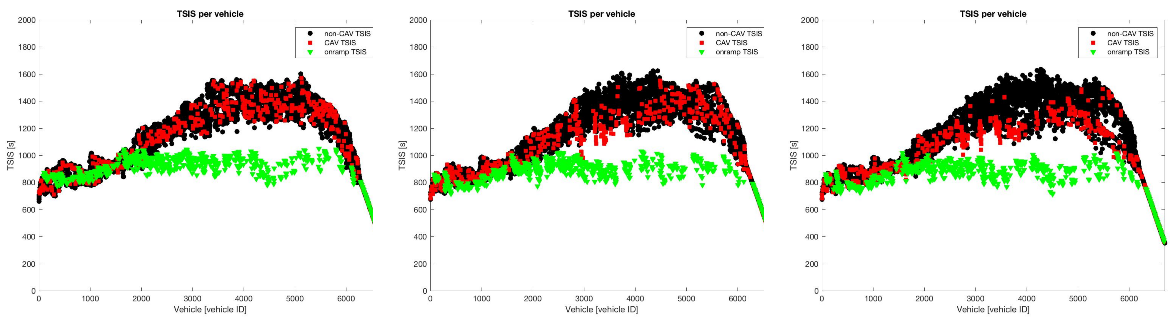

Figure 6. – The individual vehicle time spent in the system of 10% CAVs. The left figure shows the control ("no") strategy, the middle figure shows the strategy with an one-time density threshold check and the right figure shows the strategy with a permanent density threshold check.

Conclusions

The results show that the active platoon formation strategies work as they were intended, they actively form platoons while the capacity drop does not increase. However The TSiS for the conventional vehicles in the congestion does deteriorate (per vehicles on average 200 seconds). This does not seem a lot and the CAV platoons will probably stabilise traffic conditions further downstream, since they are platooning with small inter-vehicle time gaps. However, the perception of the driver in the conventional vehicle might be different. They would see moving vehicles, while they are stuck in a slow moving traffic jam. This might instigate the drivers and they could disregard the restriction on the left lane. This would not only make the strategies inefficient, it could also be dangerous (e.g. rear-end collisions). To improve the model and mitigate any problems, the following recommendations are made.

Recommendations

The recommendations are twofold, they were made for the road manager or Rijkswaterstaat (RWS) and for further research and development.

Recommendations for Rijkswaterstaat:
Although the public use of CAVs is not allowed on the motorway yet and it will still take some time before the CAV penetration rates are beyond 2% of the Dutch motorway (assumption according to ACC penetration rates) (Rijkswaterstaat, 2016), it is advised to prepare for the scenario where CAVs do go beyond this level of penetration.

The suggestions that should be incorporated in this script to facilitate the developed strategies, primarily concern legislation issues. Rijkswaterstaat should:

1. Allowing CAVs to drive on the public roads.
2. Allow CAV identification signalling lights.
3. Handle CAV responsibility issues (by communication with the manufacturers).
4. allow conventional vehicle identification for V2V (and V2I) communication (a privacy matter).
5. Allow real-world tests that can validate the scenario with 0% CAVs with the DDLS activation strategy with an one-time density threshold check. This can be done by shutting down the left lane in a traffic jam with a fixed bottleneck.

In particular the road authorities (RWS) should make it easier to perform tests with CAVs on the motorway, this would allow further validation of the simulation models.The strategies showed promising platoon formation results, but even if these specific strategies will never be implemented, the suggestions will still be valid. Most of the suggestions concern a legislation change, it is wise to consider these suggestions for when the "age of the CAVs" is present.

Recommendations towards further research and simulation model development:
The recommendations for further research an model improvement are threefold:

1. Improve the simulation model by ensuring the strategy is controlled by a centralized control system. This system would improve the strategy in efficiency, increase the simplicity to use the model and increase its flexibility (i.e. implementation of other scenarios)
2. A strategy with a fixed bottleneck due to a lane drop should be researched, this is believed to have minimal disadvantages.
3. With the centralized controller a combination with these strategies and COSCAL (v2) (Mahajan et al., 2015) should be developed, this could increase throughput and prevent the delay in TTSiS.

Furthermore tests on the safety of these strategies should be performed, to indicate whether or not the propagation speed of the jam is dangerous.

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List of Abbreviations

IV	Intelligent Vehicle
CAV	Connected and Automated Vehicle
CC	Cruise Control
ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
DDL	Dynamic Dedicated Lane
DDLS	Dynamic Dedicated Lane Section
DLS	Dedicated Lane Section
AD	Automated Driving
SAE	Society of Automotive Engineers
LMRS	Lane-change Model with Relaxation and Synchronization
IDM+	Intelligent Driver Model (+)
ABS	Automatic Braking System
AS	Activation Strategy
GUI	Graphical Users Interface
TSiS	Time Spent in the System
TTSiS	Total Time Spent in the System
RWS	Rijkswaterstaat
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
I2V	Infrastructure to Vehicle

1. Introduction

A traffic jam is a phenomenon known world wide. Many people try to avoid it, yet few ever succeed. The implementation of intelligent vehicles (IVs) might solve or reduce the traffic jams in the future. Many studies hint towards a solution with IVs, in particular using Cooperative Adaptive Cruise Control (CACC). This is an application of the connected and automated vehicle (CAV). These vehicles are connected by vehicle-to-vehicle (V2V) communication and are able to follow each other with smaller time gaps than conventional vehicles. The act of automatically following a leader vehicle with a group of vehicles is called platooning. Platooning with CAVs in congestion is very hard to achieve, however, congested traffic could benefit greatly from vehicle platoons with low inter-vehicle time gaps. In order to exploit the ability of the CAV to drive in a platoon with small inter-vehicle time gaps, this study searches for a strategy that forms CAV platoons in congestion with traffic that also contains conventional vehicles.

1.1. Background of intelligent vehicles

The mass production of automobiles, a concept that was perfected by Henry Ford beginning in 1913 with the world's first moving assembly line for cars (Batchelor, 1994), kick-started the evolution of the car: seatbelts, air bags, automatic braking system (ABS) and a built-in GPS system are mere examples of this process. These ongoing evolutions ensure the user has a safer and more comfortable ride. For evolutions in vehicle automation, the society of automotive engineers (SAE) has developed levels of automation, the so called SAE levels of automation (SAE Committee, 2016). An overview of the levels of automation is given in Appendix A, these SAE levels are a well known standard by which the level of automation can be measured. A higher level means more automation and responsibilities for the system, a lower level means the human driver is more in control.

The evolutions in automation result in IVs like ACC and CACC equipped vehicles that (only) focus on the longitudinal driving behaviour[1] (this goes up to SAE level 2). For a full autonomous or rather (Shladover, 2005) automated vehicle (AV), the vehicle needs to take over all driving tasks. This starts when all driving tasks are controlled by the automated driving system, but the fallback of the dynamic driving tasks is still in human hands (SAE level 3) and it ends with the automation of all driving tasks (SAE level 5), resulting in a fully automated vehicle. In order to differentiate between different levels of vehicle automation and guide the development, this SAE level structure was developed.

Whilst the vehicle level of automation is indicated with the aforementioned SAE levels, the behaviour of automated vehicles and the interaction of automated vehicles with its environment is indicated by a hierarchical architecture for vehicle automation (Shladover, 2005). This hierarchical structure is shown in figure 1.1, it has five different layers and schematically shows the interaction between the layers in an automated network system, below an

[1] Although vehicle systems also incorporate lateral automation (e.g. Lane Keeping Assistance), the focus lies with longitudinal driving behaviour.

explanation is given.

The network layer is the top layer of the system. This could be a large urban region containing different links. The links would contain different coordinated vehicle groups (e.g. platoons or other interaction(s) between vehicle groups) and each group is formed by multiple vehicles operating in the regulation layer. The individual vehicles contain different physical attributes. This bottom layer is called the physical layer.

So far, vehicle development by the big manufacturers incorporates automation that is only part of the regulation layer of this hierarchical structure. This report focuses on a strategy development that resides in the higher coordination and link layer. However, the operation of the individual vehicles is still described by the regulation layer, therefore an understanding of the systems operating in this layer is required.

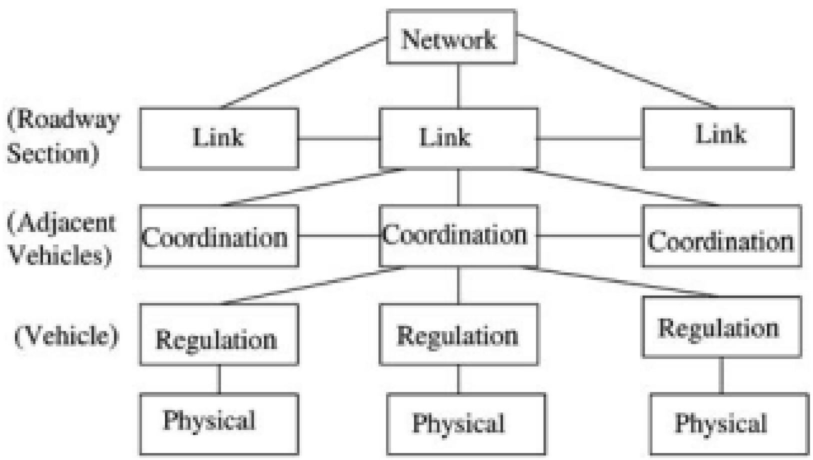

Figure 1.1. – Hierarchical architecture for vehicle automation (Shladover, 2005).

As said the ACC and part of the CACC systems (SAE levels 1 and 2) operate in the regulation layer, these are therefore explained in the subsections below. The urgency for CAV deployment is also elaborated, which gives a better understanding of the problem of congestion on the Dutch motorway network. To facilitate the initial[2] CAV deployment, the possibility of dedicated lanes is researched, this concept is explained in subsection 1.1.4 below.

1.1.1. ACC, the predecessor of CACC.

The explanation of ACC starts by the explanation of cruise control (CC). With CC the vehicles can maintain a constant speed while the driver does not have to touch the gas pedal. Cruise control is a well known automated driving function, while ACC is not that

[2]This is the deployment of CAVs considering the first (percentages of) CAVs in the car park of the Netherlands.

well known by the general (Dutch) public (Prick, 2017). However, the explanation of adaptive cruise control is quite simple: ACC is cruise control that adapts its speed in CC mode to maintain a fixed distance gap. That way a safe distance to the predecessor is guaranteed by a **variable** time gap whilst the speed of the vehicles is taken into account.

1.1.2. CACC vehicles

What if the automated vehicles can anticipate to (multiple) vehicles that are beyond the first predecessor? Essentially, that is exactly what CACC vehicles do. Instead of a variable time gap, the vehicles communicate with each other via V2V communication (Wilmink et al., 2007; Van Arem, 2013), which results in a communication controlled time gap (a **fixed** time gap). This thesis assumes a fixed time gap of 0.7 seconds for the CAVs in a platoon (as according to Ploeg et al. (2014)). This allows the CACC vehicles to drive in platoons with smaller inter-vehicle time gaps than ACC equipped vehicles, allowing traffic flow to improve and stabilize (van Arem et al., 2006; Pueboobpaphan and van Arem, 2010). An added benefit of driving in platoons is the reduction in fuel consumption (Wang et al., 2017b), which benefits the environment. This thesis assumes full CACC capabilities for the CAVs that are implemented in this thesis.

The longitudinal following behaviour of the CAVs belong in the regulation layer, but the abilities that let the CAVs communicate with each other resides in the coordination layer. When the CAVs communicate with the network there is a collaboration between the link layer and the coordination layer.

1.1.3. The urgency for CAV deployment

The travel time delay on the Dutch motorways increased by 10% in 2017 compared to 2016. Historically seen this is quite high, but last year (2016) the increase in travel time delay was twice as high (22%) (KIM, 2017). It has to be said that various reasons resulted in a decrease in this travel time delay over the decade before (2005-2015) (new asphalt, new infrastructure and also a decrease in traffic (due to the economic crises), but this decrease cannot be sustained since the main method of more asphalt is not viable any more. This is due to the costs, the environmental issues and the limited space available. The increase in travel time delay is a result of congestion on the motorway caused by an increase in demand. Congestion poses a threat to the reliability of the network, moreover the economy is also directly affected by the traffic jams. The costs of the delays are up to 3.7 billion each year and these costs are expected to grow (due to the increase of delays) (van der Aa, 2017).

In short, the continuous demand for mobility together with the limited supply of road capacity, creates traffic congestion. There are two possibilities to deal with this: accommodate the increase in flow or decrease the flow (Bertini and Hoogendoorn, 2012). Accommodating the increase in flow can be achieved by traffic management and the usage of CAVs, decreasing the flow can be done by demand management (e.g. inflow restrictions by ramp-metering etcetera).

This study tries to accommodate the increase in flow. If vehicles can use the capacity more efficiently by following each other by a smaller time gap, the capacity of the road would grow relative to the shrinkage of the time gap. This argument is valid, considering a well known formula which states that flow [vehicles/hour] equals density [vehicles/km] times speed [km/hour] (or by the equation: $q = k * u$). Since speed is required to remain the same (in order to have no increase in travel time), the vehicles have to get closer to each other (more vehicles per kilometre) to accommodate the increase in flow. Platooning with CAVs is a great strategy to achieve this, however the deployment of these vehicles has not even begun.

An estimation of the time line in which these vehicles will be deployed on the motorway is given by Dokic et al. (2015), shown in figure 1.2. This figure represents the time line of two scenarios, an evolutionary and a revolutionary scenario. For the evolutionary scenario, the development and introduction of automated driving (AD) will steadily go through every level of automation. The revolutionary scenario intends to take the vehicles to a higher (or the highest) level of automation in one development step.

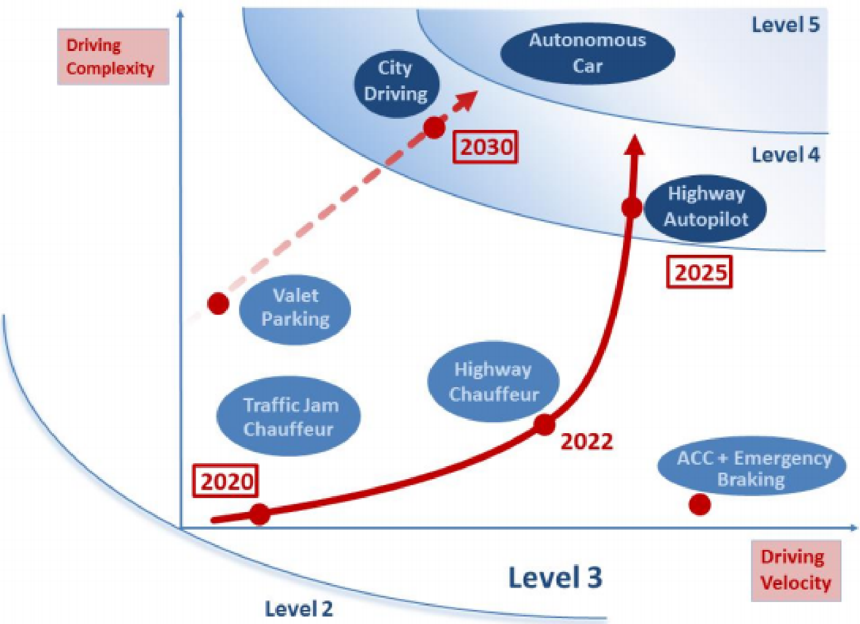

Figure 1.2. – Time line in which automated driving will develop for the evolutionary scenario (solid line) and the revolutionary scenario (dashed line) (Dokic et al., 2015).

1.1.4. Dedicated lanes for CAVs

An idea to deploy the CAVs on the motorway could be by using a dedicated lane. Such a lane can let one specific type of vehicle drive on it and it has been introduced in the Netherlands before. Multiple studies have been done with dedicate lanes for automated vehicles (Hall and Caliskan, 1999; Eskafi et al., 1992; Varaiya, 1993; Godbole et al., 1995; Agre and Clare, 1993). Therefore the so called intelligent vehicle highway system (IVHS) is a well known subject that comes along with automated vehicles. The disadvantage for this system is the exclusivity of the asphalt. The high construction costs of such a system make it not feasible nor desirable to implement. A less intrusive method exists, i.e. a dynamical aspect can be implemented on existing lanes. An example of this system is the new peak-hour lanes (in Dutch "spits stroken"), these can be switched "on" and "off" (whatever is required). A combination of both would create a dynamic dedicated lane (DDL) for IVs.

Thus, besides the normal purpose of a motorway lane, it can be allocated to different purposes. Using a dedicated lane in order for CAVs to actively platoon is not a far-fetched idea. How the DDLs will be used in the active platooning strategy is laid out in sections 3.2 and 3.3. These two sections explain the main body of the active platoon formation strategy.

1.2. The problem definition

The aforementioned evolutionary progress that kept people safe(r) and comfortable in combination with economic growth, caused a great demand for travel by car. This "need" is the cause of congestion. Progress also means that intelligent vehicles are on the rise and commercial deployment of CAVs is about to happen. These CAVs create possibilities that could accommodate the traffic flow, which in turn can reduce travel time delays, congestion and environmental issues. This research is focussed on the formation of CAV platoons on the existing motorway structure for the initial deployment of the CAVs. This could diminish the capacity drop created by congestion, increasing the throughput downstream due to the small inter-vehicle time gaps of the created CAV platoons.

"Forming CAV platoons 'on' the motorway in congested and mixed traffic, without the deterioration of the traffic conditions, is the problem this research attempts to solve."

There are three subjects that together form the problem definition: **on** the motorway platoon formation, mixed traffic and congested traffic. These are elaborated below.

Mixed traffic: Studies on platooning with CAVs have been performed before (Hsu et al., 1993; Godbole et al., 1995; Varaiya, 1993; Xiao et al., 2014), but these were all with a penetration rate of 100% CAVs, meaning every car could communicate with each other. Therefore they do not tackle the first problem that CAVs have to deal with when deployed for the first time, namely: mixed traffic. Mixed traffic conditions are conditions that have "normal" (human driven) vehicles as well as (C)ACC vehicles present on the motorway network. Other studies do research mixed traffic, but only analyse the effect of it (on the throughput, platooning formation or on other traffic conditions) (Huisman, 2016), van Arem et al. (2006). IVHS was mentioned before (in subsection 1.1.4) and also Shladover (2005) suggests that the separation of mixed traffic is necessary, placing automated vehicles on dedicated separate lanes (IVHS). Hence, all of these studies do not solve the problem of:

"Forming a platoon of CAVs in mixed traffic, which predominantly contains human driven vehicles."

Congested traffic: Studies that do research platoon formation in mixed traffic conditions (Wang et al., 2017a; Van Maarseveen, 2017; Bang and Ahn, 2017) do so in uncongested free flow conditions where the platooning occurs passively or "on-the-fly". This means that the CAVs look for each other and when in range will slowly drive towards each other, but they do not actively form a platoon (e.g. waiting for another CAV to form a platoon.). The difference between active and passive platoon formation is further elaborated in 2.4. Passive platoon formation can be beneficial for the environment and upcoming traffic jams (in terms of throughput). However, it has a hard time forming platoons inside an actual traffic jam. Benefits from this form of platooning, in near congested conditions, requires a large penetration rate of CAVs (larger than 40%) (van Arem et al., 2006). Actively forming platoons in congested conditions, could benefit the throughput. Why the active platoon formation should take place in the traffic jam **on** the motorway is elaborated below, in the last element of the problem statement. For now the second element of the problem is shown, namely:

"Forming a platoon of CAVs in congested traffic, without further deterioration of the traffic conditions."

Formation of platoons on the motorway: The search for a platoon formation strategy **on** the motorway, in the aforementioned congested traffic conditions, is necessary. There are two main reasons for forming platoons, increasing traffic flow and reducing fuel consumption (Wang et al., 2017b). This research focusses on forming platoons without deteriorating the traffic conditions. Therefore the purpose of platooning in this research is: accommodating the increase of the traffic flow. If there is no congestion, reducing fuel consumption might be the main reason to form platoons. The platoon formation could also have secondary traffic flow benefits (e.g. traffic flow stability) (Amoozadeh et al., 2015; Pueboobpaphan and van Arem, 2010). It is important to make the distinction between purposes (reducing fuel consumption or traffic flow increase), because the platoon formation strategies will differ for both purposes.

For the fuel saving purpose, there are no objections to form platoons by rallying alongside the motorway (e.g. alongside a gas station, a resting place, etcetera). When the increase[3] of traffic flow on the network is to be achieved, the traffic flow is near (or at) its congested state[4]. A traffic flow increase cannot be achieved by platooning alongside the road, because if you let them rally alongside motorway, the platoons need to be put on the road again. The required merging movement, will disturb the (near) congested traffic flow even more (special manoeuvres (Mathijssen, 1989)), leading to a greater traffic flow deterioration. This argument presents the last element out of which the problem statement is build, namely:

"Finding a strategy that actively forms CAV platoons ***on*** *the motorway."*

Because there is no platoon formation strategy, the impact such a strategy has on the traffic state also needs to be researched. This is done according to chapter 4 and the results

[3] Or at least no decrease!
[4] i.e. you cannot increase traffic flow when there are free flow traffic conditions.

are analysed in chapter 5.

1.3. Research goals: the objective and the research questions

In order to research the problem stated in the previous section (section 1.2), a research objective is presented. The objective is to be obtained by giving an answer to the sub research questions.

1.3.1. Objective

In order to improve traffic conditions in terms of travel time delay, congestion and throughput, this study will try to develop new platoon formation strategies for CAVs in mixed traffic while the traffic is congested. The developed strategies will be experimented upon to see whether or not the strategy works and to research the impact of the new platooning strategies on the traffic state.In one statement the objective of this research presents itself as:

Develop platoon formation strategies that allow the CAVs to form platoons on the motorway in mixed and congested traffic, without deteriorating the traffic conditions.

The benefits should outperform the negative (side) effects. Therefore, this objective should be reached with the following sub-goals taken into account:

1. This strategy should decrease (or at least not increase) the low outflow present after the bottleneck, which is also known as the capacity drop. This phenomenon is empirically observed by and noted by numerous studies and the drop in outflow ranges from 3 to 18 percent (Yuan et al., 2015).

2. Platoon formation with CAVs in mixed traffic (with a low penetration rate) and in congested conditions, must become possible without leaving the motorway. This is essential to prevent further deterioration of traffic conditions caused by weaving and lane changes (Mathijssen, 1989).

3. During the formation of the CAV platoons, the stability of the flow in the traffic jam should not decrease (Amoozadeh et al., 2015). Hence, the traffic congestion must not get any worse.

It is important to know exactly what the implemented strategy does with the traffic flow (sub-goal 1) and the traffic conditions (sub-goal 2 & 3). Therefore the simulation experiments will research the effects of the strategy on the outflow and on the total time spent in the system (see chapter 4).

The general objective, with the help of the sub-goals, is aimed to solve the aforementioned problem. The effects of the strategy are determined by the analysis of the experiment. This objective is tried to be reached by answering the research questions stated below.

1.3.2. The research questions

The questions below state a multitude of research questions that try to achieve the objective and build up the research approach as shown in section 1.4. The questions are focussed according to the scope as described in section 1.5. Research questions 1 to 3 are answered in the literature study (chapter 2), question 4 is answered by the description of the different platoon formation strategies (chapter 3), question 5 is answered in the chapter on the simulation experiments (chapter 4) and question 6 is answered by the results of the experiment and the discussion thereof (chapter 5). All of the answers are brought together in chapter 6, containing the conclusion and the recommendations.

1. **What is the state of the art knowledge on platoon formation strategies and platooning strategies with CAVs considering the hierarchical architecture for vehicle automation (Shladover, 2005) and what are the knowledge gaps that prohibit platoon formation on the motorway in the aforementioned conditions[5]?**
    - What platoon formation strategies exist? What are state of the art platoon formation strategies can be implemented **on** the motorway?
2. **What traffic flow management theories can assist in the development of a new active platoon formation strategy?**
    - Can anything be learned from traffic flow management solutions that can be incorporated in the development of platoon formation strategies?
    - What are the main characteristics of a traffic jam?
3. **What is the best simulation model that can simulate a CAV and in the same time be used to develop an active platoon formation strategy?**
    - Which simulation models exist that can simulate traffic on a motorway?
    - What are the simulation model requirements of this thesis research?
4. **How does the active platoon formation strategy work?**
    - Considering the findings of the literature review on past technical solutions[6], what elements are implemented to develop a strategy?
    - What are the network and vehicle operation requirements for the active platoon formation strategy to work?
    - How does congestion contribute to this strategy?
    - How does mixed traffic influence the platoon formation strategy?
    - What are the limitations of the simulation model and the vehicle capabilities in the simulation model?
5. **What output from the simulation experiment is relevant to explain the effects of the developed platoon formation strategies?**

[5]The mixed traffic and congested traffic conditions

[6]The findings consider: the workings of the CAVs, traffic flow management solutions and platoon formation strategies

- What are the relevant key performance indicators (KPIs)?
- What could the impact of the platoon formation strategies be on the traffic conditions (hypothesis)?
- How do the independent variables affect the KPIs?

6. **What do the results of the experiment show about the negative effects, the benefits and the efficiency of the active platoon formation strategies?**
   - What is the impact of CAVs in mixed traffic (with conventional vehicles)?
   - What is the effect of the strategies on the KPIs?
   - What does this say on the effectiveness and relevance (worth) of the platoon formation strategies?

1.4. Research approach

An approach to explore the research questions is presented in this section. Every step of the approach shows which questions (by number) will be answered where (by chapter) and it presents the expected results or products from each step. The following approach, is taken:

1. **The literature review.** *Questions 1 to 3, will result in:*
   - A deeper explanation of the specific hierarchical layer levels, according to which this chapter categorizes its content.
   - An overview of the chosen CAV type, presenting the possibilities, weaknesses and platooning behaviour.
   - Different platoon formation strategies, active and passive, that can (partly) be implemented in the strategy development.
   - Different traffic management solutions, that can (partly) be implemented in the strategy development.
   - The typical characteristics of traffic jams, in order to better understand and mitigate the problems that come along with this traffic state.
   - An exploration of the different simulation models. This results in the best option to simulate CAVs in mixed & congested traffic, whilst being able to test the implemented platoon formation strategy in the model.
   - An overview of state of the art research that presents new ideas and insights. This overview also presents the problems with platoon formation with CAVs in mixed and congested traffic, which in turn presents the research gap(s) belonging to those problems.
2. **The Strategy development.** *Question 4 will present:*
   - The strategy development, where the use of a dedicated lane in mixed and congested traffic is proposed.
   - A network description in which the strategy can function properly.

- A full strategy description to actively form platoons of CAVs in mixed & congested traffic.

3. **The simulation experiment set-up.** *Question 5 will result in:*
    - The experimental set-up for the model, presenting three types of variables, namely: dependent, independent and control variables.
    - A simulation set-up for the platoon formation strategies, adopting and implementing tuned variables for the set-up of the strategies.
4. **Results and discussion & Conclusion and Recommendations.** *Question 6 will present:*
    - The results of the simulation experiment, expressed in the dependent variables (also known as the KPIs).
    - A discussion that analyses and interprets the results.
    - A conclusion and a recommendation that will finalize the report, answering the research questions and proposing recommendations for further research.

The visual representation of the research approach is seen in figure 1.3 containing the four elements mentioned above. Also showing the divisions of the main topics in the inner rectangles. It shows each step in the approach. This visual representation gives a good overview of the approach that will be taken for this MSc. thesis. After this overview the scope (section 1.5) of this thesis is presented.

1.5. Research scope

As shown in the introduction, certain limitations to the research have been set. The scope summarizes and clarifies assumptions and limitations made, creating a framework in which this research is done.

- The capabilities and characteristics of a CAV are assumed to be working properly according to the definition of a CACC vehicle (beterbenutten.nl, 2017; Van Arem, 2013). This means it can drive with minimal latency according to the latest technologies (Wifi-p instead of 3/4G).
- Along with the previous item, the technical capabilities of a CAV are assumed to be in order. The technical infrastructure and the V2V communication is failure proof and in good working order.
- Human factor issues presented by van Lint et al. (2016) are assumed not to be a factor in this research, that means that distractions for the human driven vehicles are not in order. Thus, the CAV does not bother the human driven vehicle and the learning curve, on how to cope with CAVs, is assumed to be completed. i.e. The human driven vehicles react to CAVs as they would to conventional human driven vehicles. In addition to this, the simulation model does not incorporate valid mental models to take care of reaction time and sensitivity to stimuli (e.g. the appearance of a CAV on the motorway.).

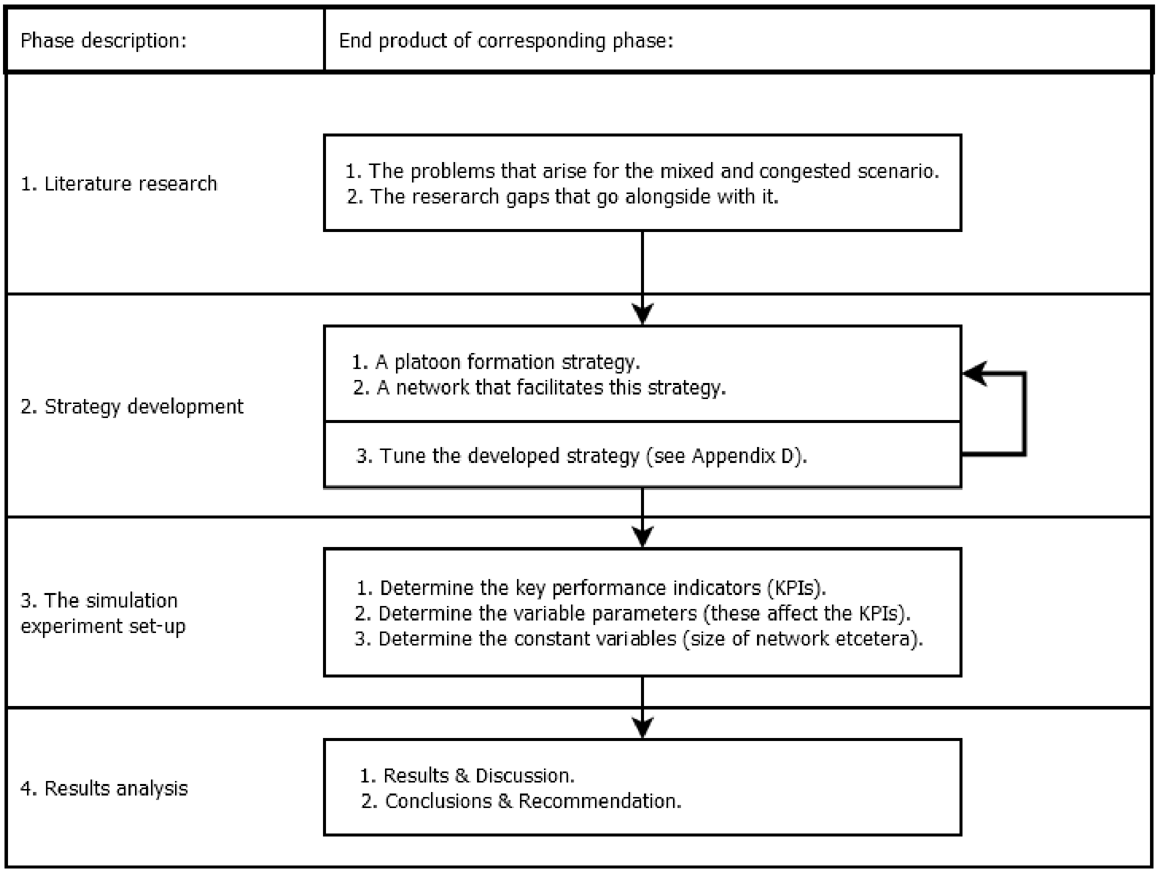

Figure 1.3. – Research process, rectangles show the main topics out of which each approach step (chapter) consists.

- This research is focusses on motorways. As expected, as shown in figure 1.2, the implementation of CAVs are to be expected to be on the motorway first.
- This research focusses on near congested and congested conditions only. Where there is a fixed bottleneck present on the motorway (Treiber et al., 2000).
- Four types of vehicles are used: A conventional vehicle, a light truck, a (heavy) truck and the CAV. According to the SWOV report with index numbers for freight traffic (Tromp, 1997) the trucks will be responsible for 10% of the traffic, this is slightly rounded down (from 11%).
- For each of the vehicle types, the same mean of the properties are used, weight, acceleration, etcetera. A stochastic differentiation determining the exact properties.
- New government rules need to work along with CAV deployment, this will not be an obstacle, therefore at least:
    1. The legal matter needs are solved, meaning the CAVs can drive on the Dutch motorways. (e.g. law on tailgating, automated hands-free driving, etcetera).

2. CAV detection devices with vehicle specifics are compulsory, according to the advice of Huisman (2016).
3. CAVs have recognisable features for other traffic (e.g. human driven, autonomous and ACC vehicles.)
4. Limit merging behaviour by conventional vehicles by government ruling, with the help of the previous item.
5. The communication infrastructure has nation wide coverage for the required wireless communication from vehicle to infrastructure (V2I) and vice versa (I2V).
6. Not only the I2V communication is in order, the infrastructure is deemed still understandable by human drivers. i.e. matrix signs need to be adapted to human usage.

- Without a strategy CAVs will platoon on-the-fly[7] and at random, meaning that destination or speed properties will not be taken into account in the platoon formation process.
- The evolutionary scenario towards AD is adapted in this research (see figure 1.2).
- Any needs from the infrastructure for the automated vehicles has been researched by a expert group of TNO and Royal HaskoningDHV (Morsink et al., 2016). This report concluded that extra investments in the road network are required to make the roads available for both automated vehicles and human driven vehicles, it is assumed that these investments are made and remaining questions regarding the infrastructural needs are resolved.

1.6. Outline of thesis

In this outline the content of this thesis is given at chapter level and the contributions made by this Master thesis are described.

1.6.1. Thesis Content

Below a list of content at chapter level is included, describing the content of the thesis:

1. This introduction.
2. The Literature review, what is out there right now.
3. The platoon formation strategies.
4. Simulation experiments of those strategies.
5. The results and a discussion of the results.
6. A Conclusion and recommendations.

[7] Within a certain distance a CAV will drive towards the leader

1.6.2. Contributions

This thesis contains research directing towards new platoon formation strategies. These strategies allow CAVs to form platoons in congestion at the first stages of the deployment of the CAVs. This results in more efficient platoon formations with CAVs at (very) low penetration levels. The effects this strategy has on the traffic state is also tested.

2. Literature review

The literature study is critical to gather an understanding of essential topics related to this research. These topics create a framework where state of the art research and the knowledge gaps come together. Within this literature study framework, the possibilities to develop a new platoon formation strategy in mixed and congested traffic are revealed. The topics essential for this research are: Connected and Automated Vehicles (CAVs), the platooning capabilities of CAVs, an overview of existing platooning formation strategies, characteristics of congestion and the search for a suitable simulation model. Also the impacts these state of the art technologies and/or strategies have on traffic is researched. When all the topics are addressed, the knowledge obtained reveals the knowledge gap and a direction towards the development of a new strategy.

The structure of the literature study follows the essential topics mentioned above. First, in section 2.1 a general overview of previous literature is given. Then a distinction in hierarchical control layers is made (Varaiya, 1993; Shladover, 2005) (section 2.2), this paves the way for three different sections; a short section on the individual IV behaviour (section 2.3) and two more extensive sections on platoon formation strategies that resides in and between the coordination and link layers of the control layer hierarchy (sections 2.4 and 2.5). Because this study researches platoon formation strategies in congested traffic conditions, section 2.6 identifies the different traffic jam characteristics. Also a short review on the chosen simulation model is presented in section 2.7. This literature study will conclude in the section 2.8, presenting the research gap with platoon formation strategies and a summary of the research. This chapter is the cornerstone on which the developed platoon formation strategy rests (chapter 3).

2.1. Overview: previous research on automated driving

Possibilities to decrease reliability issues and travel loss hours on the main roads exist by using automated driving (AD) instead of adding asphalt. Adding asphalt brings along added costs, unwanted environmental effects and is restricted to the available physical space. Because of these restrictions, Rijkswaterstaat (RWS) searches for solutions that will make better use of the existing infrastructure. The use of automated vehicles is one of the solution directions that could be promising as shown by van Arem et al. (2006). An overview of research on automated driving in mixed and congested conditions is given first, after which the overview of the impact of AD on traffic conditions is given.

Although automated vehicles can improve the traffic conditions, previous research did show that mixed levels of automation on the road can cause serious issues (Van Lint et al., 2016; Shladover, 2005). Mixed levels of automation considers different levels of automation, according to the SAE standards (SAE Committee, 2016). The study by Huisman (2016) identifies the problems with the mixed traffic situation and presents a possible solution in the form of a recommendation. It suggested that lower (SAE) level vehicles should be equipped with communicative devices, that can be detected by the CAVs, this way a CAV can effectively use its cooperative adaptive system (Shladover et al., 2012). However, this lets them merely detect the other vehicles, it does not increase the length nor the number of the CAV platoons on the motorway. Various master thesis studies were executed taking the mixed traffic situation in consideration (Huisman, 2016; Van Maarseveen, 2017; Schoenmakers, 2018), but they only mitigate or mention the problem, they do not (attempt to) solve it without altering the current infrastructure state of the Dutch motorways in congested traffic. Besides platoon formation in mixed traffic, congestion poses another serious threat. In this traffic state lane changing and other special manoeuvres deteriorate the traffic conditions even more (Mathijssen, 1989), but at the same time these manoeuvres are necessary to form platoons with CAVs.

There are many studies performed that propose a platooning strategy with CAVs. Examples are the studies of Varaiya (1993); Hsu et al. (1993); Godbole et al. (1995); Hall and Caliskan (1999). However, these did not contain the situation of mixed traffic. While it has been shown that vehicles (automated guided vehicles) can already drive fully autonomous (Versteegt and Verbraeck, 2002), human intervention and constant awareness is still required (by the law) on the Dutch motorway. Meaning that the automation level operating on the motorways is not allowed to go beyond SEA level 1 (excluding experimental tests (beterbenutten.nl, 2017)).

As soon as the vehicles become cooperative and when higher levels of automation are reached, which according to Dokic et al. (2015) will happen in the coming years (see figure 1.2), a period with mixed levels of automation on the Dutch national roads will begin. Different levels of automation with CAVs and non-CAVs will exist along each other. For this period feasible platoon formation strategies for CAVs in mixed traffic conditions need to be explored.

Impact of ACC and CACC

First various studies on the impact of ACC and CACC vehicles are reviewed. The impact of ACC is not straight forward. Using ACC on a long stretch of road that is not busy and has no extraordinary circumstances, can have a positive "resting" effect (Hoetink, 2003) for the driver and a stabilizing effect on the surrounding traffic (Van Arem et al., 1996). However, once the conditions become extraordinary: the traffic is congested or the sensors don‘t work perfectly any more (rain), the ACC vehicles have a negative effect on the throughput and is susceptible for failures that require (dangerous and quick) take-over requests (Hoetink, 2003). A couple of reasons that these negative effects exist are: system failure, sensory failure[8] and the large time gap in front of the ACC vehicle (to control its longitudinal movements). The last reason of failure could be dealt with by the deployment of CACC vehicles.

CACC equipped vehicles will allow vehicles to reduce the time gap between the vehicles between 0.3 and 0.7 seconds (Ploeg et al., 2014). They allow vehicles to anticipate on traffic beyond their own predecessor. van Arem et al. (2006) showed that with a penetration rate of at least 40% the effect of CACC equipped vehicles is positive on the traffic flow. Various other studies also showed positive effects of the CACC vehicles (Amoozadeh et al., 2015;

[8]Both system and sensory failure will not be taken into account in this thesis as prohibited by the scope (section 1.5).

Wilmink et al., 2007; Pueboobpaphan and van Arem, 2010). With the inter-vehicle time gap values mentioned before and the latency of the communication considered, the platoon stability is determined at 10 vehicles in a platoon. Otherwise the platoon will become unstable (Shladover, 2005; Amoozadeh et al., 2015).

The research (only) implements a CACC algorithm in order to be used in a higher control layer, according to the control hierarchy presented by Varaiya (1993) and Shladover et al. (2012). Where the CACC controller is in between the regulation and coordination layer, the focus of this research lies on the development of a strategy that works in between the coordination and the link layer as can be seen in the next section. In these layers an active platoon formation strategy can be developed (see chapter 3).

2.2. Division in three hierarchical control layers

The core of the literature study is structured according to the hierarchical control layers. This structure creates a clear division in specific layers of control in which a platoon formation strategy is developed and explain in what layer the strategy would operate. This layer system was first introduced by Varaiya (1993) but the explanation of Shladover (2005) connects better with this research, this structure can be seen in figure 2.1. There are three layers in which the subjects of "**CAVs**" and "**Platooning**" reside. Researching or developing CAV capabilities, is not in the scope of this research, but it needs to be mentioned because it is an essential element in platoon with CAVs. The explanation of the capabilities of a CAV reside in the regulation layer (within the bottom red box). The **active** platoon formation strategy resides in one or even two levels higher, the coordination and link layer level. In these levels an active platoon formation strategy will be developed (chapter 3). The difference of an active or a passive platoon formation strategy is explained in section 2.4 alongside an overview of different platoon formation strategies.

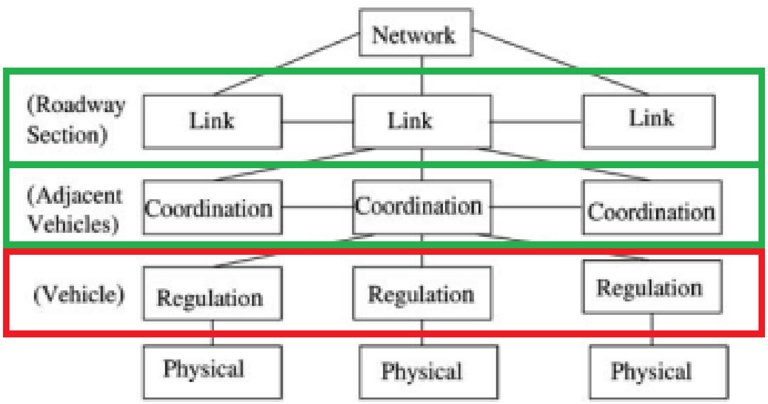

Figure 2.1. – Hierarchical architecture for vehicle automation by Shladover (2005)

The paper of Shladover (2005) describes the layers starting from the bottom and moving up:

1. At the regulation layer the control of the vehicle itself is found, including lateral and longitudinal control.

2. The coordination layer ensures the vehicle trajectories. As Shladover et al. (2012) said: *"Manoeuvres are coordinated among adjacent vehicles."* (e.g. lane changing and joining a platoon).

3. At the link layer the focus shifts towards managing traffic flows. The paper explained: *"balancing traffic across lanes, metering the entry rate of vehicles to maintain good local traffic flow, and assigning suitable speed limits to each lane."*

This clearly indicates the focus of this literature research. The next three sections in the literature research are done according to this structure. The regulation layer that this research adopts is described in section 2.3, the various platooning strategies that exist in the coordination layer are described by the review in section 2.4 and in section 2.5, traffic flow management studies are reviewed.

2.3. The regulation layer: How does a CAV work

Many studies on platooning with CACC go into depth considering the regulation layer level, however, this is not the focus of this research and therefore this section shortly discusses the (C)ACC strategy that is *implemented* in this research. This section shows the literature from which the following behaviour of the CACC and ACC originated. Researching the CAV following behaviour generates a better understanding of the operations at the coordination and link layer level. The work on the ACC controller by Shladover et al. (2012) and the work on the CACC controller by Wang (2014) which has been implemented and altered by Van Maarseveen (2017) is elaborate enough to be implemented by this research. It explains the behaviour of a CAV in the simulation and shows the limitations and benefits with the assumptions and choices made. The relevant ACC and CACC controllers are explained graphically in figure 2.2 and are elaborated in the paragraphs below.

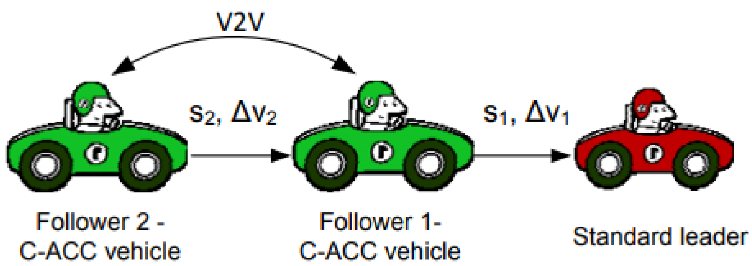

Figure 2.2. – A multi-anticipative CACC controller (Wang, 2014)

ACC: Shladover et al. (2012) discusses an ACC controller that determines the acceleration of the ACC vehicle, i.e. the leader of the CAV platoon. It does so according to a desired speed or according to a certain distance gap control, depending on the distance towards its predecessor (above or below 100 m). This research uses an ACC system for the leader of the CACC platoon and it has a fixed **time** gap control set at 1.5 seconds. In section 3.5.2 the operational algorithms for the ACC behaviour of the individual CAVs are described.

CACC: The thesis study of Van Maarseveen (2017) explained multiple approaches of a CACC platooning strategy. Eventually a strategy with a constant time gap (CTG) controller is chosen, which communicates with its predecessor by a multi-anticipative controller as was suggested by Wang et al. (2016). The operations of the CAVs are according to the combination of the two controllers and is shown in figure 2.2. As with the CACC control algorithm for the vehicle behaviour, the CACC algorithm of the individual CAV behaviour is explained in section 3.5.2. These algorithms are based on the work of Van Maarseveen (2017) and thus Wang et al. (2016).

2.4. Traffic flow control in the coordination layer

As said before, this research focusses on platooning in the coordination layer and beyond. The regulation layer "only" describes the behaviour and algorithms of the individual CAVs.

An important issue that is relevant to the coordination layer for the coordination between CAVs, is the term "string stability" as extensively explained by Ploeg et al. (2014). When the CAVs are in following mode, the followers in the platoon need to react to the predecessor (to speed changes). Platoon stability is explained as:

"Platoon stability is whether the speed disruption will grow over the vehicle number in the platoon. In platoon stable traffic, the disruption will reduce, in platoon unstable traffic, this disruption will grow." (Pueboobpaphan and van Arem, 2010)

Various studies show that string stability can be obtained by a maximum platoon size of 10 vehicles (CAVs) (Amoozadeh et al., 2015)(Shladover, 2005).

Besides the V2V cooperation, this research searches for a method to let CAVs cooperate with the infrastructure as well[9]. This separation of platoon responsibility is the reason for a sub division in platoon formation strategies, namely:

- Passive platoon formation strategies.
- Active platoon formation strategies.

Because you can also plan ahead with platooning, a distinction in pre-trip platooning and on-trip platooning can also be made. However, only one example is found to perform pre-trip platooning, and the difference is clearly explained in the description, therefore a separation on this topic is neglected.

[9] One could argue that this resides in the link layer level, it is at least closely related with the link layer level, see section 2.5

The responsibility of platoon formation with passive platoon formation strategies, lies solely with the CAVs and their cooperation among each other. With active platoon formation strategies, this responsibility is shared by the cooperation between the infrastructure and the IVs. Passive platoon formation only resides in the coordination layer, whilst active platoon formation lies between the coordination and the link layer. This part of the literature overview gives the state of the art platoon formation strategies: active and passive. The literature on (smart) infrastructural solution and ideas is incorporated in the next section (2.5), describing traffic flow management in the link layer.

Different platoon formation strategies
In this sub section active and passive platoon formation strategies are described, after they are divided by pre-trip and on-trip formation strategies.

Overview of platoon formation strategies from literature:

- **Passive strategies:**
  - *On the fly platooning.* Only when a CAV is in the neighbourhood (e.g. 150 meter) of another CAV, the CAVs will try to close the gap in between (Van Maarseveen, 2017; Wang et al., 2017a; Broucke and Varaiya, 1996). This kind of this platoon formation strategy is very commonly adopted.
  - *Spontaneous mixed platooning.* Spontaneous (passive) platooning where the vehicles can self organize their platoons **in** a mixed traffic situation. This is done by "autonomous[10]" vehicles (Agre and Clare, 1993).
  - *Platooning by swarming.* Bird flocking and fish schooling are two examples of swarming, this looks as if it is situated in the regulation layer, however in this study this strategy is used to form platoons (Bang and Ahn, 2017). This is a specific type of "on the fly platooning", a depiction of the strategy is given in Figure 2.3.
- **Active strategies:**
  - *Destination celled platooning.* In order to create an order in the way of platooning, this platoon formation strategy suggests to form platoons by order of the destination with the help of inter-platooning cells (see Figure 2.4) (Xiao et al., 2014).
  - *Stopping alongside the road*[11]. This uses the capacity possibilities provided by the network, it plans to platoon as with *"planning in order to platoon"*, but it plans during the trip and with normal vehicles.
  - *Dedicated lanes to form platoons.* As presented in subsection 1.1.4, much research has been done to form platoons by the means of a dedicate lane also known as the intelligent vehicle highway system (IVHS) (Godbole et al., 1995) (Varaiya, 1993) (Eskafi et al., 1992) (Hall and Caliskan, 1999). This dedicated lane is a permanent dedicated lane, that cannot be used by conventional vehicles.

[10]The difference between autonomous and automated is that, autonomous is fully self reliant and thus, does not communicate with other intelligent vehicles (Shladover, 2005)
[11]This is an idea of the writer of this research, based on *planning to platoon* by Bhoopalam et al. (2017)

– *Planning in order to platoon.* This identifies that steps have to be taken to reap the benefits in the early phases of the IV deployment. It proposes a framework for trucks to plan their journey in a platoon. Basically this is platooning in advance Bhoopalam et al. (2017).

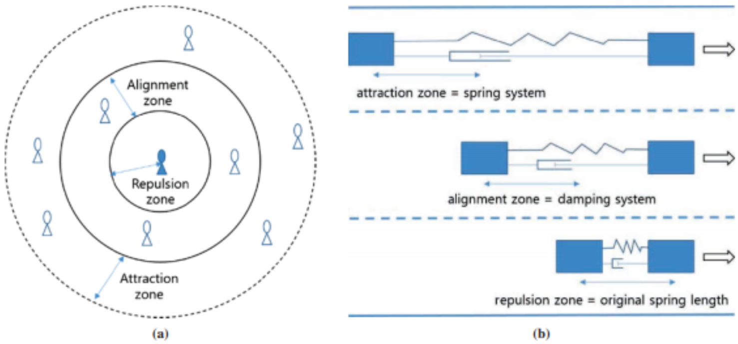

Figure 2.3. – Swarm intelligence: a fish schooling (a) (Couzin et al., 2002) and matching zones for CAVs (b) (Bang and Ahn, 2017)

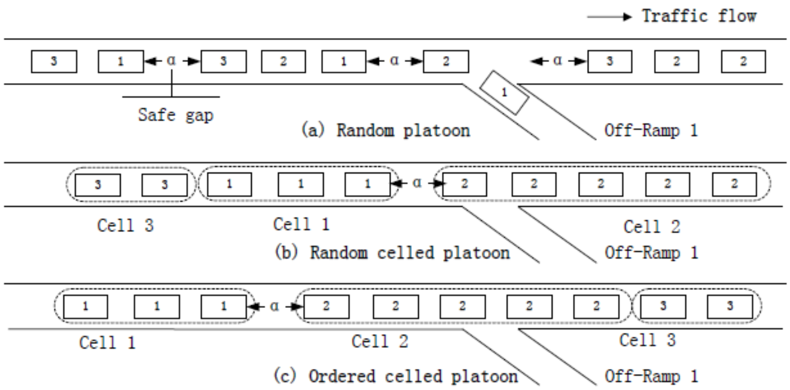

Figure 2.4. – Two strategies in the form of destination celled platooning, random and ordered (Xiao et al., 2014).

None of the aforementioned platooning strategies arrange for the CAVs to form platoons while in congestion within mixed traffic. Agre and Clare (1993) propose a passive strategy with autonomous vehicles, but this is likely to reduce traffic flow (Huisman, 2016). These vehicles do not communicate with each other and are likely ACC performers, that work alone (autonomous).

2.5. Traffic flow management in the link layer

Traffic flow management is taken care of in the link layer level of the hierarchical architecture for vehicle automation. Possibilities of implementing traffic flow management solutions into an active platoon formation strategy should not be overlooked, since the motorway is the element, present in the link layer, on which the CAVs drive. Any solution direction, by this literature review, that could help develop a platoon formation strategy should be taken into account.

There are a couple of traffic flow management solutions reviewed that could present a solution for the described problem (section 1.2). The first review of an implementation of traffic flow management is the dedicated lane. Examples are carpool lanes, the freight specific lanes and the bus lanes. All have (or had) different purposes, but the principle is the same, the use of a dedicated lane that can only be used by one vehicle type. Already many studies on the deployment of IVs mention the use of an intelligent vehicle highway system (IVHS) (Godbole et al., 1995; Hsu et al., 1993; Varaiya, 1993; Eskafi et al., 1992; Hall and Caliskan, 1999). However, a dedicated lane for a automated type of vehicle has not been implemented (yet). The negative side of such a highway system is that separate infrastructure is required, increasing the costs and space usage.

Another approach, currently implemented in the Netherlands is the peak-hour lane ("spits strook") which is a lane that is only used when certain conditions uphold (e.g. certain time or traffic flow). In the Netherlands this is implemented by the dynamic (matrix) signs above the road. The signs dynamically change the availability of a lane. These signs can also adapt the speed and give traffic information.

A system called "COSCAL (v2)" (Mahajan et al., 2015) (or previously "SPECIALIST" (Hegyi et al., 2008)), makes use of these dynamic signs to reduce the speed right before a traffic jam ensuring traffic stability. By the means of preventing further spillback by the cause of the wide moving jam (it stops the jam wave travelling upstream), it decreases the capacity drop.

This review of traffic management solutions in the link layer level, presented two main topics. 1. The use of a dedicated lane. 2. The use of dynamic signalling. The use of one or both solutions, could be part of the platooning strategy.

2.6. Characteristics of a traffic jam that influences with platoon formation

The problem statement (section 1.2) pointed out that the formation of CAV platoons needs to be performed **on** the road during congested conditions. Three different kind of bottlenecks can cause congestion; the fixed bottleneck, the moving bottleneck and stop and go waves (Treiber et al., 2000; Richards, 1956; Lighthill and Whitham, 1955; Treiber and Kesting, 2014). The scope (section 1.5) already stated that the congestion in this thesis is caused by a fixed bottleneck, this is done to limit the the amount of variables, hence this is the most straightforward bottleneck. For a fixed bottleneck, the head of a jam does not move forward (moving jam) or backwards (stop and go waves), but is fixed in space. A fixed bottleneck can have several causes, three examples are given:

- *A lane drop:* the road reduces the amount of lanes (e.g. from three to two), creating a traffic jam.

- *An on-ramp:* vehicles can drive on to the main motorway via an on-ramp, the extra vehicles cause congestion.
- *An accident:* this can shut down one or multiple lanes (which basically works as a lane drop), which causes congestion.

Figure 2.5 shows a fixed bottleneck at the on-ramp, it can be seen that the head of the jam is fixed in space. The bottleneck creates the traffic jam, which could be of use for a platoon formation strategy. In a platoon formation strategy the traffic jam could be used to catch the leading CAV and when following CAVs also reach the tail of the traffic jam, a platoon of CAVs could form.

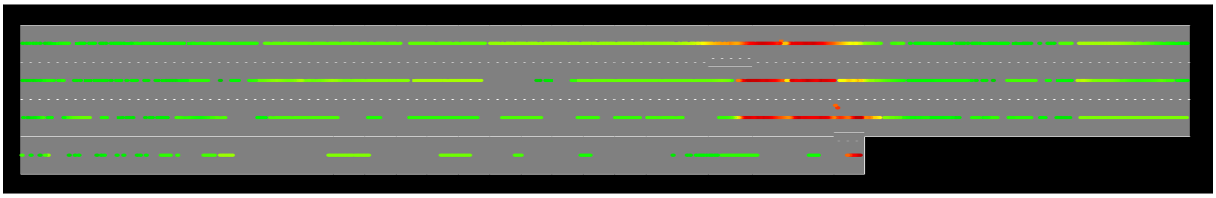

Figure 2.5. – A fixed bottleneck due to an on-ramp on a three way motorway. The colours indicate the speed; green is free-flow, red is standstill (jammed) and yellow is in between (60 km/h).

As said before, a traffic jam might be used to form platoons. Therefore the causes and characteristics of traffic jams with a fixed bottleneck are researched. The jam characteristics that could benefit or contribute to a platoon formation strategy are elaborated.Below the characteristics of congestion (due to a fixed bottleneck) are presented with a description. This description also includes possible benefits that could be used for the development of an active platoon formation strategy.

- **High density (vehicles/km)**
  - As said in section 1.1.3; flow (vehicles/hour) equals density (vehicles/km) times speed (km/hour) (according to the equation: $q = k * u$) . Therefore, if the flow (into the jam) is high and the speed is low (which is case with a traffic jam), the density in the traffic jam is also high. Typical value of jam density varies per road type (Treiber et al., 2000), but is estimated to be 35 (or more) vehicles per kilometre per lane. This value was found, in the preliminary tests (appendix D), to be the minimal value for a traffic jam to occur and sustain. The high number of vehicles per kilometre (high density) in a traffic jam creates a problem for platooning purposes but can also be of use.

    The problem is that CAVs, normally, cannot get past the conventional vehicles and thus are not able to form a platoon of more than the incidental two or three CAVs, this problem is shown in figure 2.6. This is especially the case with extremely low penetration rates. However, an opportunity appears because in actual distance, different from free flow conditions, the CAVs are all quite close to each other. This aspect could be used if the CAVs can find a way to come together quickly, i.e. if a clear (dedicated) lane was suddenly available.

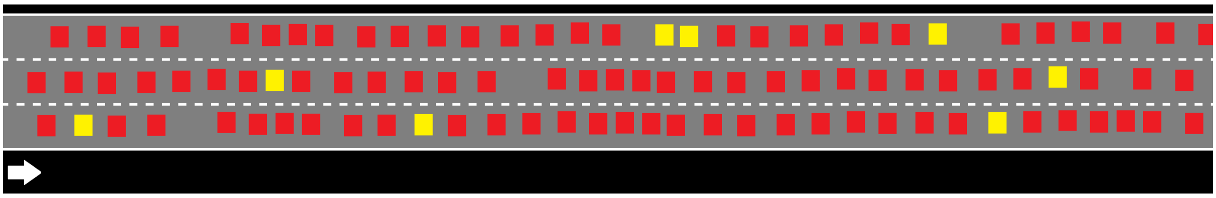

Figure 2.6. – Start of the strategy, same for both strategies, red vehicles are non-CAVs, yellow vehicles are CAVs.

- **Capacity drop**
  - The flow after the bottleneck is lower than flow before the bottleneck. There are nuances in the cause of capacity drop, however, every case of capacity drop is triggered by the high density (vehicles/km) (Chung et al., 2007). The vehicles' lane changes (in order to seek a faster lane) and the delay in acceleration by a following vehicle[12] (Chung et al., 2007; Treiber et al., 2000). This phenomenon is empirically observed by and noted by numerous studies and this drop in outflow ranges from 3 to 18 percent (Yuan et al., 2015). This study aims to prevent an increase in capacity drop compared to the base scenario.
- **Low (safe) speeds**
  - This traffic jam characteristic speaks for itself, as everybody knows the speeds in a traffic jam are low. When the speeds in a traffic jam get to near standstill, speed differences between the lanes are negligible (Kerner, 2005).

    In low and safe speeds active platoon formation can be carried out safely, without putting human lives on the line. With slow speeds and a required (safe) time gap to perform a lane change, the lane changing process requires less free space on the other lane (where the vehicle wants to go). The longitudinal distance travelled during the process is also less, due to the same principle[13].
- **Traffic flow disturbances due to lane changes**
  - This is the cause of the capacity drop (as stated above) and the cause of the traffic jam. Because the traffic state in near congested conditions is unstable, the slightest disturbance can cause a traffic jam, including lane changes that induces unnecessary braking (Mathijssen, 1989). The capacity drop can also be explained by this behaviour because a lane change requires free (so partly unused) space on one of the lanes (Mathijssen, 1989; Daganzo, 2002).

[12] The vehicle accelerating out of the traffic jam keeps a larger gap between its preceding vehicle compared to the gap it maintained in (stable) free-flow traffic.
[13] The principle stating the relationship between distance, time and speed; hence, the distance travelled is equal to the product of time spent travelling and the speed whilst travelling ($x = v * t$).

This disturbance of traffic flow could be used to actively form platoons. Since the flow is already heavily disturbed, an active platoon formation strategy **on** the motorway might **not** make it worse. An indication that an extra disturbance does not matter is given by the implementation of COSCAL v2 (Mahajan et al., 2015)). This is a traffic management strategy that creates a disturbances by actively using the matrix signs to let the vehicles slow down. However, the safety of such a platoon formation strategy in disturbed (and difficult to oversee) traffic conditions does raise concerns. The assumptions on the impact on the traffic flow and safety are partly based on common sense, this will be tested by the simulation experiments (chapter 4).

These main characteristics are essential to understand the effects a traffic jam has on the traffic conditions. It also explains, the difficulties a jam poses for the purpose of platoon formation with CAVs, after all, that is the focus of this research. This elaboration on traffic jam characteristics with a fixed bottleneck also show possibilities that could help develop an active platoon formation strategy.

2.7. The simulation model for traffic flow assessment

In order to find the best suited simulation model in which this research can perform its simulation experiments, the requirements for this research are compared with the properties of different simulation models. Therefore a list with essential capabilities that a simulation model will require for this research is shown below. This will be compared with the a review of the capabilities of different simulation models which has been done by Van Maarseveen (2017). A table summarizing this review is presented in appendix C in figures C.1 and C.2. The essential elements that need to comply with this research can be traced back to the problem statement (section 1.2), the scope of this research 1.5 and practicalities considering a Master thesis.

The problem statement: The problem at hand states: *"Form platoons with CAVs 'on' the motorway in congested and mixed traffic, without deteriorating traffic conditions"*. Therefore a simulation model has to be capable of:

- Modelling CAVs, with cooperative capabilities and modelling conventional vehicles at the same time.
- The ability to alter the traffic conditions in such a way that a fixed bottleneck can be created (by design) at the on-ramp in the network.
- The ability of the model to easily extract various data, to measure the state of the traffic conditions.

The research scope: The scope of this research dictates certain capabilities required by the simulation model:

- Modelling different types of vehicles (CAVs, normal vehicles, light trucks and heavy trucks) and accordingly the ability to alter the properties of each vehicle.

- The infrastructure is able to distinguish between CAVs and conventional vehicles, also the CAVs can recognize the conventional vehicles.

Practicalities: Besides the key elements based on the content of the thesis, the simulation model should also be practical:

- The model should be available for students.
- There is a limited amount of time that can be spend on coding, therefore the model should not be too complex.
- Support or a manual should be available.

The list of requirements above has three hard requirements, namely: the implementation of cooperative behaviour (1) and heterogeneity of vehicle properties (2) must be possible and the simulation model must be available to use. Furthermore there are preferences regarding the user friendliness of the model; these consider the complexity of the model and the availability of support or a user manual.

This list is compared with the overview in the appendix (appedix C) and brings brings forward the following conclusion, Only VISSIM, MOTUS and OTS have full cooperative capabilities (longitudinal and lateral), OTS is not yet student available, thus the comparison between VISSiM and MOTUS remains. The choice for modelling in MOTUS prevails because of two key elements:

1. MOTUS is less complex, which safes time and ensures the researcher has enough programming capabilities.
2. The cooperative behaviour of the lateral movement in MOTUS is better than that of VISSIM.

Besides the key elements, MOTUS is not a 'black box', therefore a complete understanding of the underlying code of the model is possible, which leads to a better analysis of the results understanding the limitations of the simulation model.

Thus summarizing, after a careful consideration, MOTUS (TUDelft, 2015; Schakel et al., 2012) was chosen to be the simulation model for this research. MOTUS stands for: microscopic open traffic simulation and is based on the LMRS and IDM+ models (Schakel et al., 2012; Kesting et al., 2010). MOTUS fits best with the content and focus of this research. It can be implemented with different vehicle types, i.e. mixed traffic. It can control the amount of traffic and thus ensure a traffic jam at the on-ramp. It can program all of the cooperative capabilities and it is **not** a black box.

2.8. Conclusion

In this literature review an overview of previous research on automated driving was given. Extensive studies on platooning with CAVs exposed some knowledge gaps, but also presented platooning strategies and a simulation model that could be used to develop platoon formation strategies. This conclusion first summarizes these findings after which the knowledge gaps are discussed.

The goal for this literature review was to give an insight in the problem and create different ideas to solve it. Therefore it was structured to explore platoon formation strategies according to the three different hierarchical control layers for vehicle automation (see figure 2.1). Each layer defines different levels of control for a possible new strategy. In the regulation layer the control of the individual vehicle is found, this thesis assumes a multi-anticipative CACC controller described by Wang et al. (2016). The coordination layer describes the control between the surrounding vehicles determining the trajectory of the vehicles. The literature research found active and passive platoon formation strategies that gave insight in state of the art knowledge on platoon formation. This also exposed weak spots in the knowledge about platoon formation strategies, the so called knowledge gaps. The link layer described the literature about traffic flow management and their quest to solve traffic jams. This generated a deeper insight and helpful ideas to be implemented in a new platoon formation strategies, such as: The use of dedicated lanes and the use of dynamic (matrix) road signs.

Besides literature on the different hierarchical control layers, literature on a congested traffic state has also been researched. An elaborated look at the characteristics of a traffic jam will clarify the borders of the framework that has been set in the research scope (section 1.5). Also MOTUS (Schakel et al., 2012; TUDelft, 2015) was chosen as the most suitable simulation model in order to develop and test a new platoon formation strategy.

As said, the literature research on different platoon formation strategies (active and passive) residing in the coordination layer, exposed a knowledge gap. Since no other platoon formation strategies present a strategy to let CAVs platoon in congestion alongside other "conventional" vehicles, a strategy of sorts has to be developed. As Bhoopalam et al. (2017) indicated, steps need to be taken for the initial deployment of IVs, but instead of planning the platooning, a more durable strategy should be found. This is done with the majority of the vehicle types, non-trucks, in order to make the biggest impact on the improvement of traffic throughput. This should therefore take place in congestion and with the challenge of not changing the road infrastructure since that brings along large costs.

The findings along with the knowledge gap(s) demand for the development of an active platoon formation strategy. This strategy should *"let CAVs form platoons on the motorway in congested and mixed traffic, without deteriorating the traffic conditions."*. By developing an active platoon formation strategy, the infrastructure and the CAVs should cooperate, increasing the solution possibilities and the impact the strategy has on the traffic state. A new platoon formation strategy is presented in the next chapter 3.

3. The platoon formation strategy

The development of a strategy in order to actively form platoons, takes a central position in this thesis. The introduction (chapter 1) formulated the problem and the research goals. The literature review provided the theoretical background. It presented the basics and state-of-the-art knowledge and a research gap, concluding that a strategy should be developed that can form platoons in congested and mixed traffic conditions, without deteriorating the traffic conditions. That input is taken into account in this chapter, starting with the introduction that explains the development method and its implementation in this study. It describes different elements of the new platoon formation strategy; using CAVs, congestion and dedicated lanes as assets to a solution. After which the functions and sections in the network on which the platoon formation takes place is explained, section 3.2. The two new active platoon formation strategies are explained after that (section 3.3) and in the next chapter a simulation experiment is set up to perform tests on the resulting strategies (chapter 4).

3.1. Introduction: Developing a CAV platoon formation strategy

To develop a platoon formation strategy this study exercised the method known as prototyping. The figure below (figure 3.1) shows the method and its implementation in this study is explained thereafter.

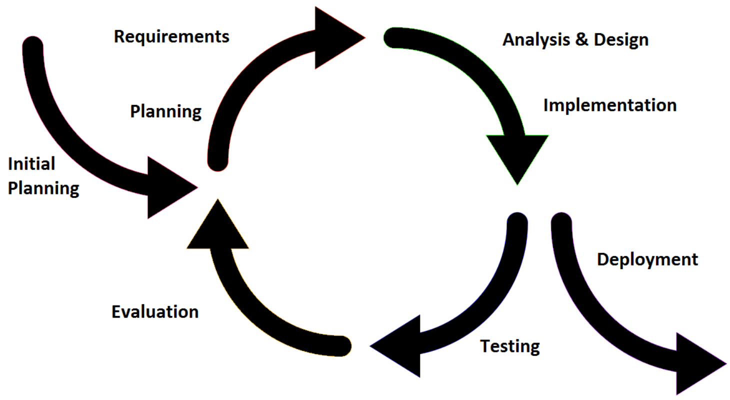

Figure 3.1. – The platoon formation strategy development method.

The steps shown in figure 3.1 that are implemented in the development of the strategy are explained below. These steps led to the *"Deployment"* which is the implementation of the finished strategy in MOTUS. This strategy is presented in this chapter (from section 3.2).

The Requirements
These are necessary demands that need to be in the design of a new platoon formation strategy. They emerged from the research goals and the research questions 3 and 4.

- The strategy should actively form platoons, even when there is a (very) low penetration rate of CAVs. This resembles the situation on the Dutch motorways after the first years of CAV deployment.
- The strategy must work in congested traffic.
- The strategy must work in mixed traffic, with CAVs and non-CAVs.
- There should be no significant increase in deleted vehicles than in the base scenario. Deleted vehicles are inherent to the simulation model in MOTUS, where the vehicles that collide or cannot find their way onto the motorway (via the on-ramp) are deleted.
- The network on which the strategy operates must take the physical Dutch motorway network structure into account.

Analysis and Design
Using state of the art knowledge and ideas generated from the literature review. The following strategy elements and ideas are proposed:

- Using dedicated lanes, that can change from dedicated to not-dedicated. Thus Dynamical Dedicated lanes (DDLs).
- Using the possibilities of CAVs and the emerged (possible) benefits of congestion, namely: High density, present disturbances and low (safe) speeds.
- **On** the motorway, active platoon formation.

Implementation, Testing and Evaluation
Every strategy design is implemented in MOTUS, preliminary tests were run with the first designs (see appendix D) and by observing the data and the graphical users interface (GUI), the requirements were adjusted/evaluated. This meant that they were specified to improve the model. After this a new round of prototyping could begin, until the strategy met the research goal(s) (see section 1.3.1). This process created a platoon formation strategy that could be implemented and experimented upon in MOTUS. A short description of the strategy is given below, after which it is thoroughly worked out in the rest of this chapter.

The Deployment: the platoon formation strategies
Two platoon formation strategies have been developed, both strategies are based on the same foundation. The platoon formation strategy applies dynamic dedicated lane sections (DDLSs) (figure 3.2, no. 5) in order to let CAVs platoon on the road in congested conditions. If the density [vehicles/km] on these lane sections pass the threshold of 41 vehicles per kilometre (Determined in appendix D), they become dedicated to CAVs only. This dedication is deactivated once the same threshold is reached on the final DDLS. The two different platoon formation strategies are: *"an activation strategy with an **one-time** density threshold check"* **and** *"an activation strategy with a **permanent** density threshold check"*.

The activation threshold for both strategies is different in matters of permanency. The lane sections in the strategy with an one-time density threshold check will remain activated once the density threshold has been reached (41 vehicles/km). The lane sections in the strategy with a permanent density threshold check, can deactivate before the last DDLS has been reached. This occurs once the density of a lane section has dropped below 35 vehicles per kilometre. When this happens the dedication for the considered section and the section up-stream is deactivated. In practice this means the platoon formation strategies deviate a lot, subsection 3.4.3 goes into depth on this difference.

The next section, section 3.2, explains the functions of the different elements of the network in this strategy (the network part of the strategy). The description of the actual operations of the strategies follows in section 3.3 (the vehicle operations part of the strategy).

3.2. The network functions description

This section together with section 3.3 describes the platoon formation strategy. This section describes the different functions of the network. With the help of a graphical representation of the network every function is explained (figure 3.2). After this functional network description, section 3.3 explains exactly how the platoon formation strategies are implemented on this network. The road layout description elaborates on the use of the essential characteristics of a congested motorway and it elaborates on the use of dedicated lanes.

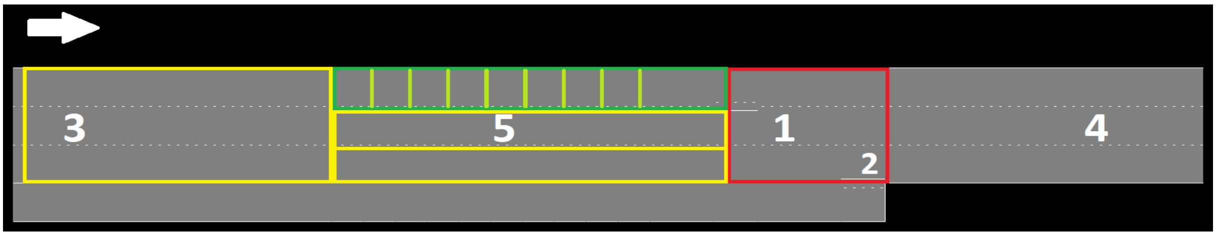

Figure 3.2. – The network layout, divided in sections that have a different function.

The layout has five distinctive network sections. The first four are *passive sections* in the network, their properties and rules do not change. The last section is an *active section*, it (dynamically) changes its dedication for CAVs when the density threshold is reached. The numbers in the figure shows the placement of the different sections in the network. An explanation of the different sections will follow the list that stands below:

1. The designated jam area.
2. The bottleneck.
3. The inflow section (high traffic inflow, causing congestion).
4. The outflow section, downstream of the bottleneck.
5. The dynamic dedicated lane sections (DDLSs).

1. The designated jam area: the designated jam area in figure 3.2 is shown by the red area, containing number 1. It represents the predetermined length of the designated jam area, that precedes the start of the DDLSs (the green area with number 5 below it). The jam area has two functions:

1. *To form platoons*: by "catching" the CAV leader, slowing down the leader with the traffic jam, the following CAVs can close in and form a platoon.

2. *To prevent an increase of the capacity drop*: by making the designated jam area long enough[14] the area will contain a traffic jam as long as the strategy is active. Ensuring that, when the strategy is deactivated, the conventional vehicles can close the gap that was created by the clearance of the dynamic dedicated lane sections.

2. The bottleneck: The bottleneck is caused by the on-ramp, where it meets the main road at number 2 in figure 3.2. Normally such a bottleneck is unwanted, due to the traffic jam it creates, however in this research this bottleneck is used for the purpose of platoon formation. Therefore, in order for the on-ramp to create a big enough bottleneck (bottleneck strength) the on-ramp (in combination with the main motorway) should have a high enough demand. This demand should ensure a traffic jam for all scenarios (scenarios with different CAV penetration rates). Preliminary tests have shown that 1100 vehicles per hour is a large enough on-ramp demand to ensure a traffic jam. This traffic jam should be a fixed traffic jam, where the head of the jam does not propagate (backwards nor forwards). The function of the bottleneck is to fill the designated jam area with a traffic jam, this will "catch" the CAVs which will lead to the formation of CAV platoons.

3. The inflow section of traffic on the main road: This represents the inflow section generating the inflow of traffic on the main road. The inflow on the main road should represent near congested traffic conditions and should be enough to create a traffic jam in combination with the on-ramp demand at the location of the bottleneck. This inflow is presented in table 4.1 and is non-linear, which is aimed to represent a typical congested demand pattern (Goemans et al., 2011).

4. The outflow section: The outflow section downstream of the bottleneck. The flow can be measured here which gives an indication on how well the strategy is working or disrupting traffic. If platoons are formed, the outflow should increase because platooning CAVs follow each other with a smaller time gap.

5. The dynamic dedicated lane sections (DDLSs): The DDLSs are shown in figure 3.2 at number 5, the left lane sections in the green boxes become dedicated. The dynamic dedicated lane is divided in eleven sections of 500 meters, which is the minimal distance between each matrix sign (Rijkswatersaat, 2017). Only the first (most downstream) DDLS has a length of a 1000 meters this corresponds with the minimal length of a lane drop (Rijkswatersaat, 2017). The functions of the DDLSs, for all three lanes, are four fold:

1. As a dedicated lane. The lane is dedicated to CAVs only.

2. As a normal lane. All vehicles can use this lane.

3. As an "ON" trigger. When the strategy should begin activating the first, most downstream, DDLS. If a density of 41 vehicles per kilometre has been reached **on the mid-**

[14] This designated jam area has a length of 2 km. This is determined by preliminary tests (see appendix D). These tests showed that the area contained a traffic jam during the entire time the platoon formation strategy was active.

dle lane the strategy is activated. This mechanism is elaborated in subsection 3.4.1. There is also an exemption for the activation strategy with "*a **permanent** density threshold check*", which is already mentioned in the previous section and elaborated in section 3.4.3.

4. As an "OFF" trigger. When the strategy should be deactivated. This happens when a density of 41 vehicles per kilometre has been reached at the last, most upstream, DDLS. An elaboration of this mechanism is given in subsection 3.4.2.

The functions of the network and the actual active platoon formation strategy interact through the DDLSs. Of course, the rule based (de-)activation of the DDLSs in the strategy is the core of the developed strategy. Therefore the in-depth explanation is devoted to the next section, in particular subsection 3.4.1 and subsection 3.4.2.

Other properties: extra measures are implemented in the network in order to keep the formed platoons together more efficiently. These two measures are:

1. A separation line between the middle lane and the left lane in the designated jam area (see figure 3.2) right after the DDLSs area (area number 5). This is to make sure no conventional vehicles can cut into the platooning vehicles.

2. When the DDLSs are activated the allowed speed is reduced to 50 kilometres per hour. This helps the CAVs come together even more, but is also ensures a safe speed where the CAVs will enter the tail of the traffic jam. Another benefit is that the conventional vehicles will no longer cut into platooning vehicles right after the deactivation of a lane section. This is caused by a lower incentive for non-CAVs to use the left lane since there is no speed gain and therefore no speed gain incentive (LMRS model) (Schakel et al., 2012). More on this topic in subsection 3.5.2 .

Every section is described and their function in the strategy is explained. In order to narrow down the size characteristics of the network, the next chapter describes the exact network layout (see section 4.4). The variables relevant to the strategy are pre-calculated and determined according to the Dutch road network.

3.3. Macroscopic description of the CAV platoon formation strategies

This section describes the two developed strategies on a macroscopic level. It describes the exact processes that take place in each strategy. Both strategies are executed on the network that was described before. First the description of the strategy through a flowchart is given. In the "Flowchart explanation" the details of the flowchart are explained. The description and the flowchart describe the processes of the strategies on a macroscopic level.

Section 3.4 explains the strategies‘ more complex processes. The strategies processes are looked at in depth, at a microscopic vehicle level, the exact differences of the two strategies are thereby explained. The strategies should be evident at the end of that section.

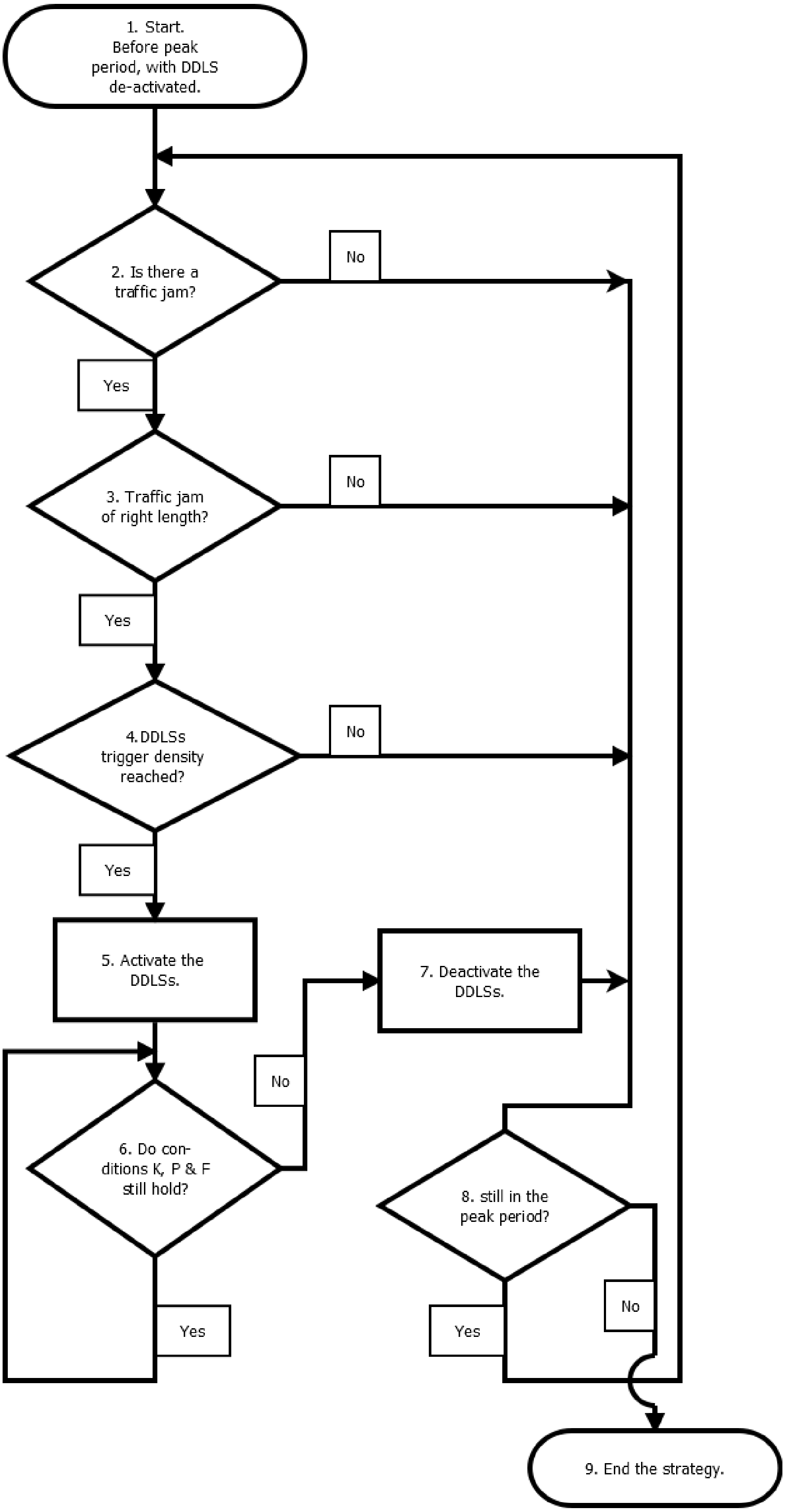

Figure 3.3. – Flowchart

Flowchart explanation:

1. Start with the right initial start values, namely:
   - With the DDLSs deactivated, thus with normal road conditions.
   - Right before the peak period, at 6 am, without congested conditions.
2. Is there traffic jam with a fixed bottleneck present? Propagation of the head of the traffic jam is not allowed, not upstream nor downstream.
3. There are two limits for traffic jam length:
   a) Is the traffic jam long enough (larger than 2 kilometres as explained in section 3.2) that the traffic jam can "catch" the CAVs? This ensures no capacity drop.
   b) Is the jam short enough that it does not pose a threat for spillback onto the previous upstream on-ramp? (For the length elaborations, see appendix D.4
4. Density [veh/km] is a good indicator for the presence of a traffic jam. The density is the "ON" switch for the strategy, it is therefore called the trigger density. By preliminary test (Appendix D) the trigger density is determined at 41 vehicles per kilometre per lane. If the first (most downstream) DDLS reached the trigger density, the strategy is activated (go to process #5).
5. Activate the dynamic dedicated lane sections (DDLSs). Only CAVs can drive on these lane sections. The elaboration of the exact operations is written in subsections 3.4.1.
6. Whether or not conditions K, P or F are met. Three conditions to stop the active platoon formation strategies. All pre-set conditions are shortly explained below. The conditions K and P are elaborated in section 3.4, in subsection 3.4.2, condition F is evident and needs no further elaboration.
   - If condition K holds, the density on the last DDLS has **not** reached the threshold density (i.e. no traffic jam at the last DDLS). If the traffic jam **is** registered, condition K failed and the DDLS deactivating process starts (process # 7).
   - Condition P is only relevant for the DDLS activation strategy with a **permanent** density threshold check. This checks whether or not the density of the section and downstream section is still above the threshold of 35 vehicles per kilometre per lane(the determination of this "OFF"-switch is presented in appendix D). If this is not the case, go to *process #7*.
   - Condition F considers the inflow of vehicles as presented in table 4.1. Once the inflow will no longer cause congestion the strategy is deactivated. This occurs five minutes after a low enough demand has been detected.
7. If condition K or F does not hold the DDLSs are deactivated consecutively, starting at the most upstream DDLS (see figure 3.8). If condition P is no longer met, deactivate the relevant DDLSs (see figure 3.9).
8. Go through the loop again if the time is still between 6 am and 8 pm.
9. End the strategy for that period of 24 hours (that day), a new cycle will start at 6 am.

This chapter included the description of all elements in the strategy, however a microscopic description of choices 2, 3, 4 and 6 and processes 5 and 7 is given in the next section (section 3.4).

3.4. Microscopic description of the platoon formation strategies

In this subsection every process of the flowchart is considered and elaborated, except for start and termination processes 1 and 9 and decision 8 because these are as simple as presented in the "Flowchart explanation". This section presents the operations at vehicle level as implemented by MOTUS, but also how this will work in the real-world. It explains precisely how the strategy works for each vehicle and what happens per DDLS. In section 3.5 the difference between MOTUS implementation and real-world adaptation is explained. The figure below depicts the activation and deactivation phase of both strategies. The activation and deactivation phase is cut up in subsection 3.4.1 and 3.4.2. The difference of the permanent density threshold check activation strategy is explained in subsection 3.4.3.

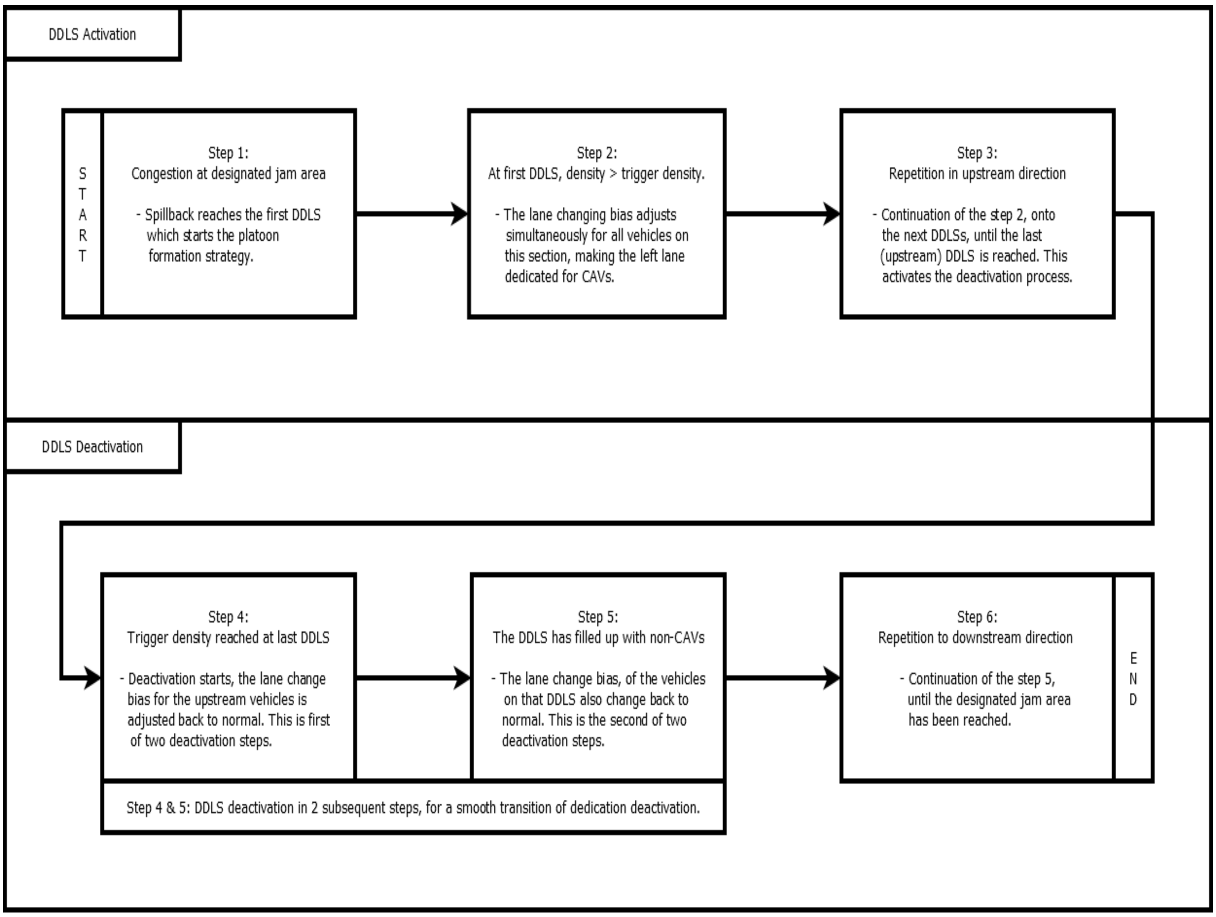

Figure 3.4. – The activation and deactivation strategy.

An example of the platoon formation strategies, as simulated in MOTUS, is shown in Appendix F, which also refers to several moving images of the strategies (YouTube): https://youtu.be/UMvCAn4Oxvc **and** https://youtu.be/i3-B-04_vHg (Hurley et al., 2018).

3.4.1. DDLSs activation strategy

This subsection explains the activation of the DDLSs, this is the first half of figure 3.4 and the choices 2,3, 4 and process 5 in the flowchart. It explains the steps in figure 3.5 per step and through a microscopic visualisation in figure 3.6.

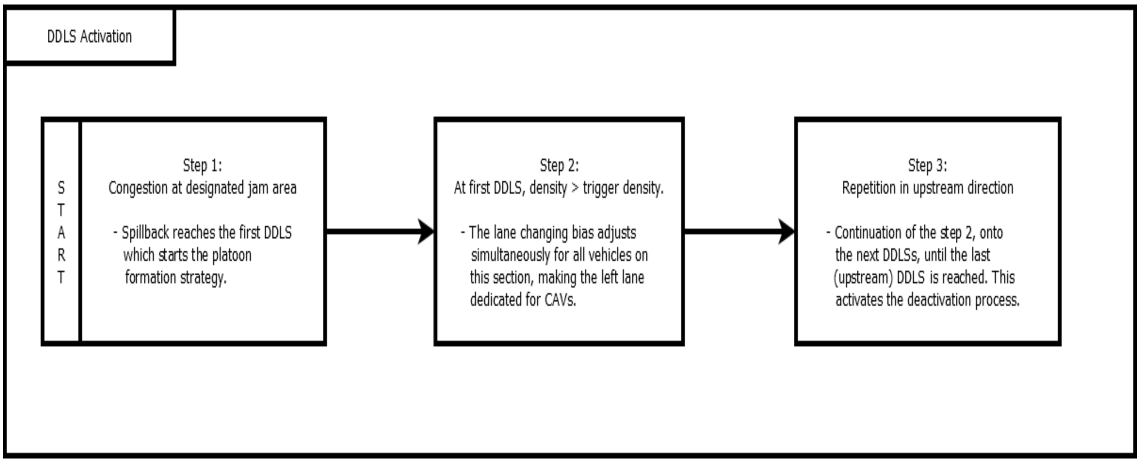

Figure 3.5. – The DDLSs activation strategy.

Elaboration of step 1 to 3:

1. The designated jam area, visualised by section 1 (A to E) in figure 3.6, has completely filled up with vehicles and there is a traffic jam of at least 2 kilometres[15] from the head of the jam, at the bottleneck, up to the first DDLS.

2. As soon as the density threshold of 41 vehicles per kilometre is reached at the first (most downstream) DDLS, this lane section is activated and becomes dedicated (figure 3.6, C2), the following activation process per DDLS is clearly visible in figure 3.6, at section D2, D3, E2, E3 and E4. In MOTUS every individual vehicle considers whether or not the trigger density is reached, that way the vehicle can determine whether or not it is allowed in that particular DDLS. In the physical world this check would be done by a central controller, making the lane section dedicated (instead of the vehicle). The condition in equation 3.1 represents the density threshold check, by which the section determines whether or not the density threshold, $k_{threshold}$, has been reached.

$$IF : k_{section} > k_{threshold}; \qquad Returns : SwitchON = \text{"}true\text{"} \tag{3.1}$$

In this equation, k represents the density and $SwitchON$ is the boolean switch (on is "true", off is "false"). If this is implemented on the actual Dutch motorway (the real-world), the lane section would be turned on. This is elaborated in subsection 3.5.1. In

[15]The minimal length of the designated jam area as explained in Appendix D

MOTUS the *"SwitchON"* condition is checked per vehicle, if the *"SwitchON"* is true, the lane change bias of that vehicles changes. The lane change bias is a value for the incentive for the vehicle to change a lane (Xiao et al., 2017). In MOTUS, at activation, the following process occurs:

"The lane change bias for the CAVs and non-CAVs change upon activation; The CAVs get a ***left lane only bias***, the non-CAVs have a ***left lane restriction bias***, ."

This process was implemented in MOTUS to ensure lane dedication and is elaborated in subsection 3.5.2. The code behind this process is visible in appendix G, that shows the conditions as coded in MOTUS (JAVA), presenting in what way the bias is altered. Section 3.5.2 explains the lateral vehicle behaviour during the lane change processes.

3. This process of DDLS activation continues until the last DDLS has been reached, this is when the deactivation process begins as described in section 3.4.2 and visualized in figure 3.8.

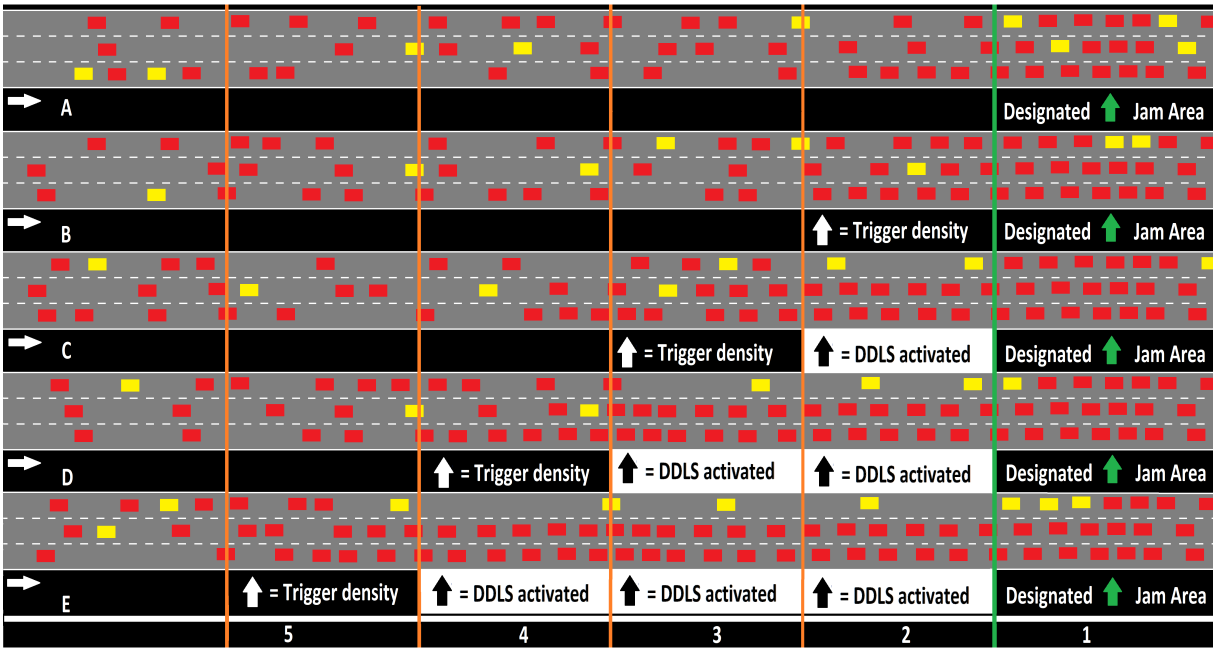

Figure 3.6. – Start of the strategy, same for both strategies, red vehicles are non-CAVs, yellow vehicles are CAVs. Motorways A to E are the same motorway at a next moment in time (A = earliest moment, E = latest moment)

3.4.2. DDLS deactivation strategy

This section explains the similarities in deactivating the DDLSs, for both strategies. The elaboration of the platoon formation strategy continues at step 4, explaining the deactivation process in detail. It consists of the second half of figure 3.4, presented below in figure 3.7.

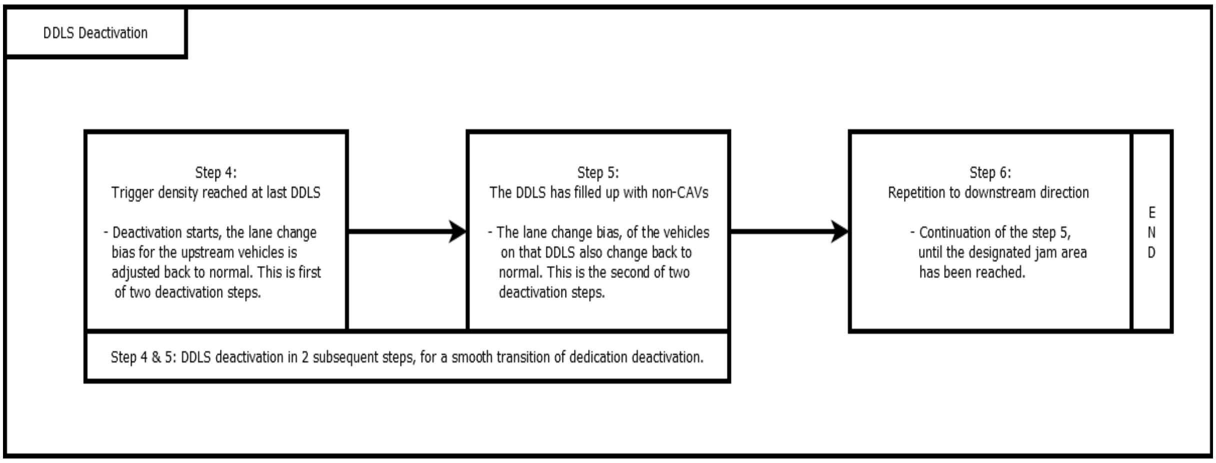

Figure 3.7. – The DDLSs deactivation strategy.

Elaboration of step 4 to 6:

4. The deactivation of the DDLSs starts when the lane dedication reached the last DDLS, meaning that all sections are dedicated up to DDLS "A9" as shown in figure 3.8 (row A). This also means that the traffic jam has reached this section (column 10), through backward propagation of the tail of the jam. When the section after the last DDLS, **A10** in figure 3.8, becomes higher than than 41 vehicles per kilometre the deactivation strategy is set in motion, this is known as the trigger density for the "off"-switch. Equation 3.2 shows the "off"-switch condition for the last DDLS.

$$\begin{aligned} IF : DDLS == DDLS_{No.10}, \&; \\ IF : k_{section} > k_{triggerdensity}; \\ Return : SwitchON = "false" \end{aligned} \tag{3.2}$$

   This should be done by implementing the first (a) of two sequential steps:

   a) The upstream vehicles (that are not on the active DDLS) are all allowed on the left lane, thus no dedicated lane section for these vehicles. This is shown by the red/white arrows in figure 3.8

5. As said the DDLS deactivation goes in two steps. When the vehicles upstream of the have filled the (previously active) DDLS, step two (b) can commence:

   b) When the upstream vehicles filled this DDL section, the vehicles are allowed to go back to the left lane again.

6. This process is repeated all the way to the designated jam area, once it arrives there the strategy is considered as "ended".

This sequential deactivation (that happens with both strategies) is clearly shown below in figure 3.8.

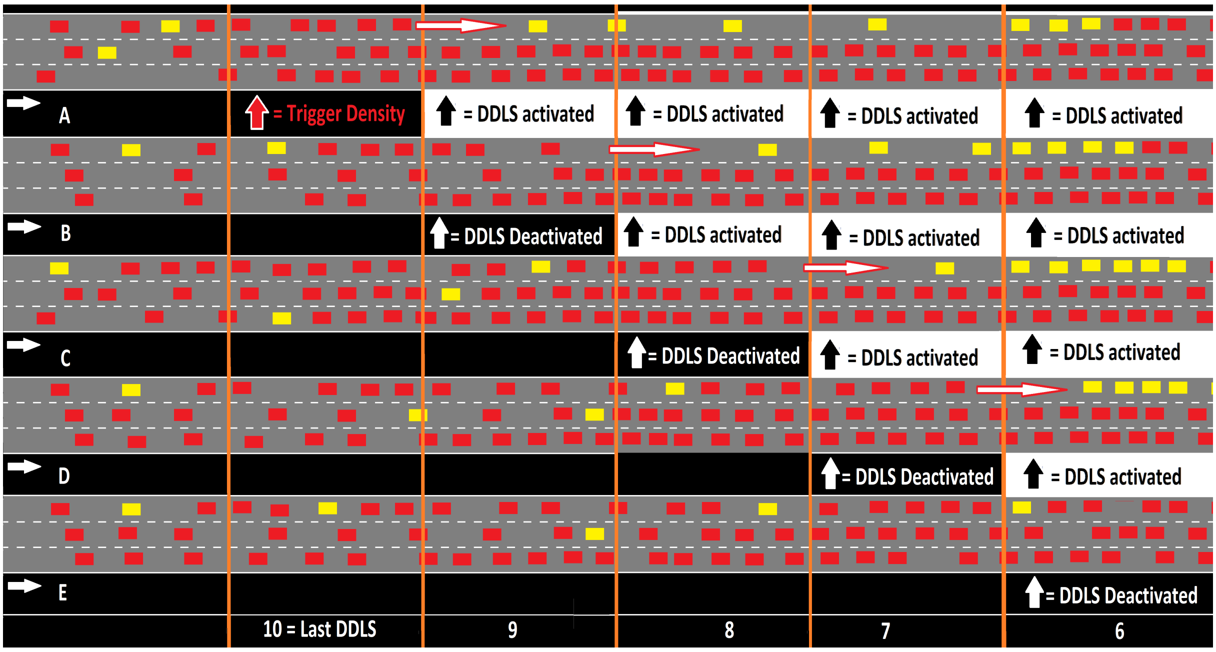

Figure 3.8. – The end of the strategy, same for both strategies, red vehicles are non-CAVs, yellow vehicles are CAVs. Motorways A to E are the same motorway at a next moment in time (A = earliest moment, E = latest moment)

3.4.3. The difference of the permanent density threshold check

The DDLS activation and deactivation process of the strategy activation with a permanent density threshold check works the same as the strategy activation with an one-time density threshold check, except for the fact that the permanent activation strategy lacks a "hold on" switch. For a section to be activated in the strategy with a permanent density threshold check, the section requires the trigger density of the section self and that of the predecessor section to **remain** above the threshold of 35[16] vehicles per kilometre. If this condition fails (the density drops below 35 [veh/km]) a process as seen in figure 3.9 is set in motion. Furthermore the density is checked in the middle lane sections, otherwise the density (on the left lane) would constantly drop below 35 vehicles per lane. This would cause the deactivation of the dedicated lane as soon as the conventional vehicles clear that lane. Summarized the extra condition states:

If the density of the middle lane is not above 35 vehicles per kilometre, the dedication for considered section and the section upstream is deactivated.

[16]For more stability in the lane change behaviour during activation and deactivation of lane dedication, this lower density (of 35 veh/km) has been implemented as a trigger for deactivation.

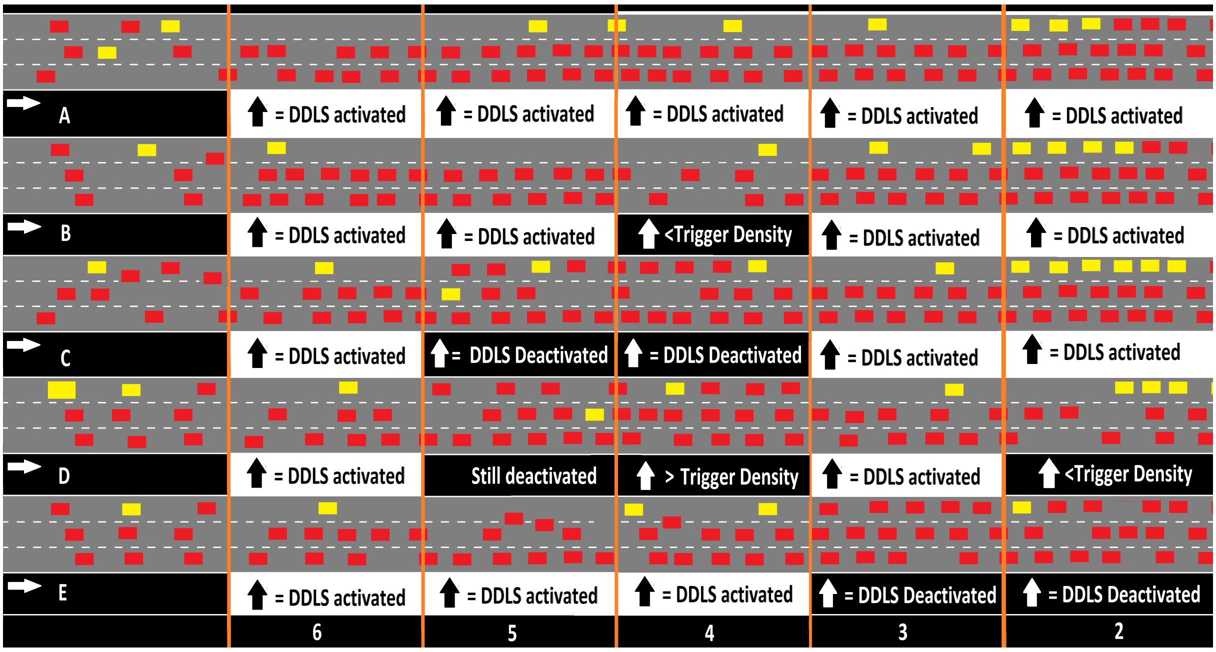

Figure 3.9. – During the DDLS strategy, the exemption of the activation strategy with a permanent threshold check. Red vehicles are non-CAVs, yellow vehicles are CAVs. Motorways A to E are the same motorway at a next moment in time (A = earliest moment, E = latest moment).

3.5. Real-world implementation vs. MOTUS simulation

To ensure a clear and intuitive description of the strategy the previous section described the strategy with real-world implementations and MOTUS simulation adaptations. In this section, the distinction between the two worlds is made. First the strategy adaptations for real world implementations are described, thereafter the behaviour of the vehicles according to the strategy as implemented in MOTUS is described.

3.5.1. Real world implementation of the strategies

Before the implementation of the strategy in MOTUS is discussed, the real world application of the strategies is explained. This section explains the activation, activated and deactivation processes of the DDLSs for both strategies. The requirements for real-world implementation of the strategies are also mentioned, see "Real-world facilitation".

For all processes the communication is key, whether this is communication to the conventional vehicle (with a human driver) or to the CAV. This communication happens between the vehicles, but also between the vehicles and the infrastructure. The communication between the infrastructure and the vehicles, in the real-world situation, **is controlled by a central command system**. This is *the* difference between the real-world implementation of the strategies versus the simulation model implementation of the strategies.

Activation
Before the activation the designated jam area is congested and the activation of the first DDLS is about to happen. A central controller registers that the threshold (of 41 vehicles per kilometre) is passed. The central controller will activate the dynamic matrix sign above the road, at the beginning of the first DDLS. This is the red-white-blue line in figure 3.10. The middle and right lane will have the conventional green arrows above the motorway. The left lane will have a (specific) red cross above the motorway. This red cross has to be recognizable for conventional vehicles, to communicate to them that the CAVs *are* allowed to drive on this road. A suggestion for this matrix sign is made in appendix L

The dynamic matrix sign at the beginning of the lane is activated to make sure the vehicles *in* the lane section reaching the threshold, do not suddenly have to move lanes, that would create sudden unsafe lane changes in very dense traffic. conditions.

The process as described above, is repeated after the next lane section passes the threshold of 41 vehicles per hour until the last DDLS (most upstream) is reached.

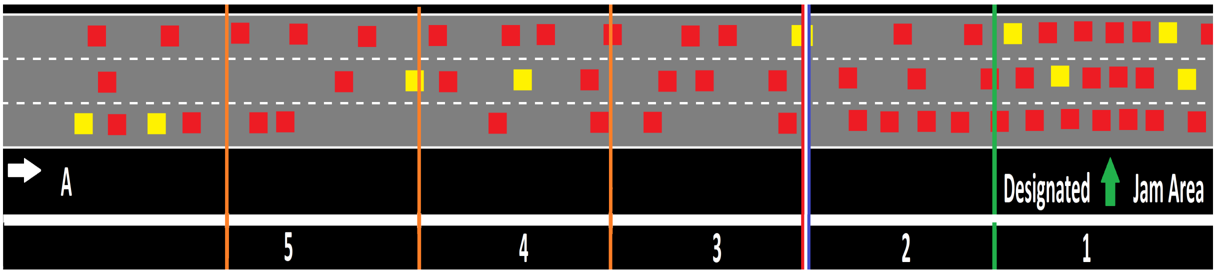

Figure 3.10. – Start of the strategy, same for both strategies, red vehicles are non-CAVs, yellow vehicles are CAVs. The red-white-blue triple line between the sections 2 and 3 are indicating a CAV only section downstream via a dynamic matrix sign.)

During activation the CAVs have to be identified. Although it is not allowed to use a light bar (as a police car would), an orange light on the top of the car could be made available by the legislator. This would ensure that a CAV is identified by the conventional vehicles who would let the CAVs merge into the left lane.

Activated
While the lane section is activated the conventional vehicles are only allowed on the right and middle lane and the CAVs are only allowed on the left lane (see figure 3.6, row E). This rule could be enforced, another option would be to inform the public with commercials that CAVs drive on the motorway and the strategies will only cause minimal delay for the conventional vehicles (see section 5.1).

Deactivation
The deactivation of the strategies would go in reverse order of the activation strategy. As seen in figure 3.11 all the vehicles coming from behind would be allowed to go on the left

lane first. This would be indicated by green downward arrows on the matrix signs over the entire cross section. When this downstream lane section is filled, the downstream middle lane section is allowed to merge to the left. To prevent vehicles from moving to the left prematurely, high fines could be installed, in combination with the aforementioned information provision (by public commercials, etcetera).

This way the gap towards the CAVs will be closed from behind and the platoons are not cut by conventional vehicles. This allows the CAVs the extra time and space to continue to form a platoon with his predecessor (which is also a CAV).

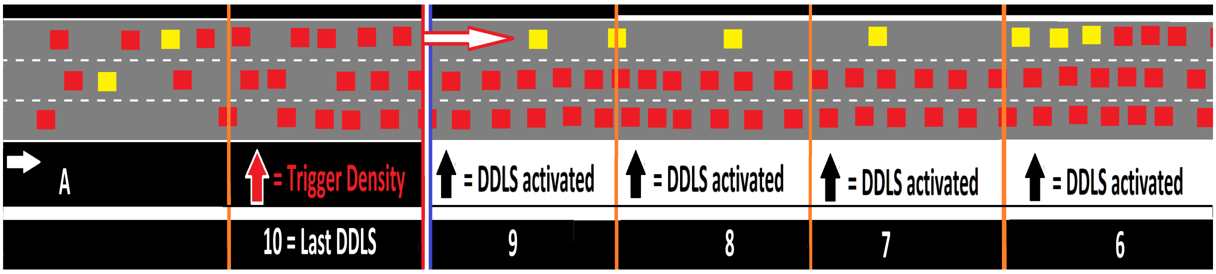

Figure 3.11. – Start of the strategy, same for both strategies, red vehicles are non-CAVs, yellow vehicles are CAVs. The red-white-blue triple line between the sections 2 and 3 are indicating a CAV only section downstream via a dynamic matrix sign.)

Real-world facilitation
The most important part of this strategy is that every object (CAVs, non-CAVs, Matrix signs, lane sections and other infrastructure) can communicate with each other. Although the V2V, V2I and I2V communication is scoped out and assumed to work perfectly, this element is underlined to emphasize the importance; the communication between elements has to work flawless and without (much) lag.

Furthermore, to enhance the safety and responsiveness, the drivers will be made aware of the presence of the dedicated lane area. Which will let them look out for the CAV identification signals.

The last element that is most important for real-world implementation is the central controller. This system will control the matrix signs after the density on a lane section is measured to pass the density threshold. The density can be measured by video (from above), otherwise the speed on a lane section is required. The speed can only be taken as a trigger if the demand of the lane sections is known.

3.5.2. CAV and non-CAV behaviour as implemented in MOTUS

This section elaborates on the behaviour of the vehicles in the strategy. This section explains the longitudinal and lateral behaviour of the CAVs and how this is applied in MOTUS. The longitudinal behaviour, defined in the hierarchical control layers as the regulation layer, is not the focus of this research. However it is a part of the developed strategy and is therefore mentioned shortly. The lateral CAV behaviour is explained as it is applied in MOTUS, it explains what happens during the activation of the strategy, during an activated strategy and during the deactivation of the strategy. The used parameters that are used for both lateral and longitudinal vehicle behaviour is explained in Appendix B.

The CAV longitudinal behaviour
The vehicular longitudinal control behaviour is as described in the literature research and is according to the implementation shown by Van Maarseveen (2017). To this extend the longitudinal CAV behaviour is explained. The conventional vehicles follow the enhanced intelligent driver model (IDM+) as incorporated in MOTUS (Kesting et al., 2010; TUDelft, 2015).

Equation 3.3 describes the ACC following behaviour that the CAV adopts when the CAV is the first (or only) vehicle in the platoon ("Follower 1" in figure 2.2). Equation 3.4 describes the following behaviour of a CAV behind another CAV ("Follower 2" in figure 2.2). This research builds on top of this implementation of a CAV behaviour in MOTUS.

$$a_{i,t}^{car-following} = k_s(s_{i,t} - s_{i,des,t}) + k_{\Delta v}R(s)(v_{i-1,t} - v_{i,t}) \tag{3.3}$$

$$a_{i,t}^{car-following} = k_s(s_{i,t} - s_{i,des,t}) + k_{\Delta v}R(s)(v_{i-1,t} - v_{i,t}) + k_a a_{i-1,t} \tag{3.4}$$

with:

$$s_{i,des,t} = v_{i,t}t_{des} + s_0 \tag{3.5}$$

$$R(s) = \frac{-1}{1 + Qe^{-\frac{s}{P}}} + 1 \tag{3.6}$$

$$a_{i,t}^{cruising} = k_v(v_{des} - v_{i,t}) \tag{3.7}$$

$$a_{i,t} = min(a_{i,t}^{cruising}, a_{i,t}^{car-following}) \tag{3.8}$$

The longitudinal behaviour, according to the equations above, are implemented and updated every 0.2 seconds the same as the time step implemented by the simulation experiment. In order to prevent collisions and ensure correct longitudinal CAV behaviour these equations are implemented in MOTUS, with: $a_{i,t}^{car-following}$ describing the desired acceleration of the CAV, $(s_{i,t} - s_{i,des,t})$ is the difference between the *actual gap* towards the predecessor and the *desired gap* towards that predecessor, $R(s)$ is a collision avoidance function described by Mullakkal-Babu et al. (2016), $(v_{i-1,t} - v_{i,t})$ is the difference in speed in comparison with the predecessor, $a_{i-1,t}$ is the passed on acceleration of the predecessor by the means of communication (CAV) and the k_s, $k_{\Delta v}$ and k_a are parameters (see appendix B).

The CAV and non-CAV lateral behaviour
The previous section (section 3.4) explains the actual lane changing behaviour in the strategy. The paper of Schakel et al. (2012) shows the implementation of lane changes when none of the strategies are active. Xiao et al. (2017) shows a way of modelling lateral lane change behaviour, by a model on motorways with CAV dedicated lanes, that can be uses for CAVs and non-CAVs (eligible and ineligible vehicles). The model of Xiao et al. (2017) formulates lane change desire based on lane change incentives, that represent mandatory and voluntary lane changes in regard to the DDLS. Below the lateral vehicle behaviour in the strategies is described. This is done according to the MOTUS implementation of lane desire according to the aforementioned lane change incentive:

$$d_{Voluntary-LaneChange} = d_{speedincentive} + d_{changeBias} \tag{3.9}$$

According to the equation above (equation 3.9) when $d_{Voluntary-LaneChange}$ surpasses a threshold, the vehicle wants to change lanes. It does so according to speed incentive and lane changing bias. The $d_{speedincentive}$ is determined by the speed the vehicle is driving, the desired speed and the speed on the other lanes (in lateral direction). The $d_{changeBias}$ is an incentive of the driver self[17].It works as follows: if the value $d_{Voluntary-LaneChange}$ for a driver is greater towards a lateral direction than for staying on the lane, then the vehicles "chooses" to go in that direction and perform a lane change.

This "choosing" whether or not to lane change can be used to make dedicated lanes Xiao et al. (2017). This is done by altering the $d_{changeBias}$ to pre-set conditions. Appendix G shows the manner in which this bias was altered and applied in this thesis in MOTUS. It shows how it changes the vehicle behaviour when the strategy is activated or deactivated.

With this information the lateral movements of both the CAVs and the non-CAVs can be explained (at the same time) as they are activated at the same time. There are three different phases for the DDLS activation strategies; "during activation", "When the strategy is active" and "during deactivation". The lateral behaviour is the same for both DDLS activation strategies for each of these phases.

During activation:
The bias is altered due to the on-switch (see appendix G), this bias then becomes the primary (and only) incentive, speed is irrelevant due to the high values of the $d_{changeBias}$ and thus a lane change becomes mandatory. For the CAVs the right lane bias becomes 0 (restricted) and the left lane bias becomes 0.9 (Almost 100% mandatory[18]). For the conventional vehicles, this is the other way around.

When the strategy is active:
During the strategy, when a vehicle is on the proper lane (left for CAVs, middle and right for non-CAVs), the CAVs simply remain left, and the conventional vehicles stay right and

[17] e.g. in the Netherlands the drivers are used to "keeping" right, but a fast driver might have another "bias", he wants to go fast in the left lane.
[18] Not entirely mandatory to ensure there are no collisions.

in the middle. When **not** on the right lane, the vehicle is ordered (by the code) to go to the right lane, this incentive is only overpowered by making sure no collision occur(0.9 instead of 1). The vehicle will even stop on the lane to make the lane change towards the correct lane. In figure 5.18 this stopping behaviour can be observed by the red dots that are not on the right lane; They hold up traffic and can only continue if they steer into the correct lane.

During Deactivation:
When the Dynamic lane sections are deactivated the vehicles no longer have this strong lane change bias, the both become irrelevant (zero) (as shown in appendix G). The speed incentive comes back into play, therefore the vehicle "checks" if the other lane goes nearer to its own desired speed. If that is the case and $d_{Voluntary-LaneChange}$ surpasses its own pre-set threshold the vehicle will perform a lane change. This is the reason that the speed is kept low with the DDLS activation strategy with a permanent density threshold.

3.6. Summary

An elaborate strategy residing in the link and coordination layer (and a cooperation between both) of the hierarchical layer structure has been presented. The method of prototyping led to a description of the network functions and the platoon formation strategies. They describe how the network and the strategy work together to activate and deactivate the DDLSs in order to reach the development objective of this study.

The developed strategy is innovative and could be the foundation on which other active platoon formation strategies can be build in the future. The following reasons explain why this is the case, in no particular order of importance:

- It is an active platoon formation strategy, where platoon formation occurs **on** the motorway and in congestion, this is the first in its kind.
- It could benefit throughput downstream of the bottleneck (because CAV platoons increase throughput). Although this should be tested in the simulation experiment.
- As soon as the first CAVs are deployed on the motorway, this strategy can be implemented. It is not necessary to wait for an increase in CAV penetration rates before this platoon formation strategy can be implemented. With this strategy the amount and weight of the platoons should increase. This should also be tested in the simulation experiment.
- This strategy does not need large infrastructural interventions.
- The infrastructure and CAV vehicles work together, but the strategy is fully focussed on the infrastructural part of the collaboration. Therefore other CAV control algorithms can be implemented in this strategy.

To summarize the strategies, they both use the traffic jam in the designated jam area, to "catch" the CAVs that are released from the traffic jam upstream. This release is done by creating a dedicated lane that can only be used by the CAVs. As soon as the trigger density is reached on a specified dedicated lane section, the section becomes dedicated. This goes on until the last DDLS is reached, then the strategy is deactivated. There are two DDLS strategies developed, namely a DDLS activation strategy:

- with a **one-time** density threshold check.
- with a **permanent** density threshold check.

The deactivation (and reactivation) strategy for both is slightly different, causing a big difference in strategies. Section 3.4 explained the similarities (section 3.4.1 & 3.8) and differences (subsection 3.4.3 of both strategies. Thereafter, section 3.5 explained the individual vehicle behaviour for the MOTUS implementation and real-world adaptation. Both CAV and non-CAV behaviour during the activation and deactivation processes of the strategy are explained in that section.

In the next chapter the experiment set-up is presented in order to test the impact of the independent variables; The determined trigger density, on-ramp demand and strategies are tested with different different penetration rate scenarios. This is followed by the results (chapter 5) to show the effect the scenarios have on the dependent variables (also known as the KPIs). These KPIs are also explained in the next chapter, section 4.2.

4.Simulation experiments

Chapter 2 provided a validated simulation model, namely MOTUS. Chapter 3, proposed two strategies in order to actively form platoons. The sub-goals for the platoon formation strategies are focussed on whether or not the positive effects outweigh the negative side effects. The purpose of this simulation experiment set up is to give a clear answer whether or not the main objective and the sub-goals are reached. Therefore, section 4.1, explains the purpose of the experiment once again. The determination of the performance indicators is done in section 4.2. Section 4.4 defines the network set up in which the experiment takes place and section 4.3 explains which variables are alternated. The necessity or purpose of setting up the experiment this way is explained in the conclusion. The next chapter analyses and discusses the results of the experiment.

4.1. An overview of the experiment

As mentioned before, the purpose of this thesis is twofold, namely:

1. Developing a strategy for active platooning in congested and mixed traffic, "on" a motorway, and
2. Testing the effects of the strategies on the traffic conditions. This is done with the performance indicators that are explained in section 4.2.

The platoon formation strategies have been explained in the previous chapter. To test the effects on the traffic conditions, a simulation experiment is set up in this chapter. The experiment will exist of 21 scenarios (see 4.3) and the result of each scenario represent the average of the six different runs of the simulation model. The simulation was done with six different seeds to ensure that, with 95% confidence, the average of each run lies no further than 3% of the mean of the average of all 6 runs (see appendix D). The simulation experiment will also expose whether or not the strategy is feasible and can be implemented on the Dutch motorways. Testing the effects of the strategies is done according to the five performance indicators presented in section 4.2.

Three types of variables
The experiment set-up is categorized by the three types of variables that exist in scientific experiments (Blakstad, 2008). The three different types are: the independent variable, the dependent variable and the constant variable. This chapter is structured according to these three types of variables.

The dependent variables, also known as the key performance indicators (KPIs), are affected by the independent variables. The independent variables are differentiated in the experiment by design. The constant variables are mentioned in the research scope (section 1.5) and were tuned beforehand (appendix D). In this tuning process certain variables were eliminated fixating the framework for this research. An example of this framework is the limitation on the expansion of the network to form platoons (due to costs). According to this framework, the network came to be. Together with the validation of the simulation model of the base scenario ("no" activation strategy), the constant variables allow the research to be interpreted accordingly, correctly, generating valid results.

4.2. The performance indicators

In order to show the feasibility of each strategy, five performance indicators are presented. These indicators also known as the aforementioned dependent variables. They represent traffic characteristics that are affected by the each strategy and the other independent variable (the penetration rate).

The indicators that are chosen are meant to present the effects of the strategies on traffic conditions and platoon formation capabilities. For each of the performance indicators below the substantiation is also given. For each scenario the different results between the strategies and the base strategy ("no" strategy) are looked at. The scenarios describe different CAV penetration levels.

1. Average platoon size, indicated by the number of leading CAVs preceding a specific CAV.
    - In order to quantify the purpose of this research, namely (active) platoon formation, an indication of the size of the platoons and an indication of the number of platoons is presented. In each simulation the CAV platoon size varies (due to conventional vehicle cut-ins). Therefore, a quantification of a platoon size is done at one specific cross section (set of lane sections connected laterally). The lane sections that are used are the sections after the bottleneck, here the platoons are released on a conventional road (no DDLSs).

      This indicator presents the maximum amount of CAVs that have driven directly in front of another CAV, which makes it possible to compare average platoon sizes per strategy. The average platoons size is: the weighed average between the size of the platoons and the number of platoons formed (including the CAVs that drive alone, in a platoon of 1).
2. Outflow (out of the traffic jam), in vehicles per hour
    - The reason why platoons are formed, as explained in the introduction of this research, is (also) to increase the traffic flow in vehicles per hour per lane. This research wants to know whether or not this actually happens. Therefore this indicator presents the outflow from the traffic jam.
3. Total time spent in the system (TTSiS), in seconds.
    - This will indicate whether or not the time spent in the system and thus in the traffic jam has increased. This shows whether or not the traffic situation (the jam) has worsened. This will be done for the CAVs and the non-CAVs alike, also presenting a visualization of the time spent in the network by each individual vehicle.

4. DDLSs active time.
    - The time that a vehicle drove on an active section, compared with the total time spent in the network. Also the amount of time a particular section is switched "on" is depicted, indicating the particular DDLS activity. Along with the platoon sizes, this indicator gives a measure of the effectiveness of the strategies.
5. Amount of deleted vehicles.
    - Deleted vehicles are inherent to the simulation model in MOTUS, where the vehicles that collide or cannot find their way onto the motorway (via the on-ramp) are deleted. This will indicate the robustness of the scenario. For example: if many vehicles are deleted **with** a platoon formation strategy implemented compared to the base scenario, it can be reasoned that the result is not valid/robust. It can also be said that more deleted vehicles is a less safe scenario, since a vehicle is deleted during due to a collision or when a vehicle cannot merge onto the motorway (via the on-ramp).

4.3. Independent variables: the different scenarios

In order to find the most optimal (and least optimal) conditions for the purpose of active platooning, four different variables are altered by design of this experiment that affect the outcome of the performance indicators. The first independent variable is the differentiation of the strategy, here the conditions that determine the dedication of the lanes are different. The other independent variables, i.e. penetration rate, the trigger density and the on-ramp demand, are simpler and are explained in their respective paragraph. This will include the reason why they are chosen to be an independent variable.

4.3.1. Differentiation of Strategy

The three strategies that are altered are: "No strategy", the "DDLS activation strategy with an one-time density threshold check" and the DDLS activation strategy with a permanent density threshold check. Each strategy is explained in chapter 3, except for "No strategy", however this strategy is the base strategy where there are simply no DDLS activation present.

4.3.2. Penetration rate

For the result regarding future scenarios the penetration rate of the CAVs is made an independent variable. The penetration rates that are varied are 0, 2, 5, 10, 20, 30 and 40 percent.

zero percent is added for each strategy to the penetration rates, as control as a validation variable. The DDLSs should still be activated, but with no CAVs present it should show on the traffic flow and speed contour. With less capacity (two lanes instead of three), the propagation of the tail of the jam should propagate faster backwards. Therefore this variable will give a validity check of the model, as is seen in appendix E. To continue, two very low penetration rates, of 2 and 5 percent, are chosen. This is to show the effects at the very beginning of the implementation of the CAVS on the Dutch motorways. After that the penetration rates increase from 10 percent until 40 percent, with increments of 10 percent.

This is done linearly to demonstrate the effect of penetration rate on this strategy with only one dynamic dedicated lane, for future implementation of this strategy. On a three lane motorway 40 percent is an extreme value, since one lane out of three lanes stays well below 40 percent (33%).

4.4. The constant variables

This section describes in what network environment the experiment is done. The physical network and the fixed demand pattern that have been set in MOTUS will be elaborated upon in this section. Also the trigger density is described in this section, this variable has been made a constant variable through the preliminary tests (appendix D.

4.4.1. The jam density threshold; the trigger mechanism

The trigger mechanism, which is the foundation of the platoon formation strategy, is the dynamic aspect of the DDLS activation strategies. This determines whether or not a lane section will become dedicated to CAVs or not. Because the active platoon formation strategy should occur in a traffic jam, the density threshold is predetermined to ensure a traffic jam at the chosen density threshold (see appendix D). According to common traffic flow theory and as seen in the preliminary tests (appendix D), a traffic jam occurs at the density of 35 vehicles per kilometre. However, the tests showed that the density of 41 vehicles per kilometre was the most robust value as an activation trigger, which would prevent premature activation of the lane dedication (this occurred at an activation trigger of 35 vehicles per kilometre).

4.4.2. Physical network

The dimensions of the physical network, for which its functions are explained in 3.2, is determined in this paragraph. This is done according to the "file top 50" (traffic jam top 50) (VID, 2017), hence a traffic jam is the basic structure behind the strategy. In appendix D.4 the top 2 motorways (A-roads), considering traffic jams, are reviewed. Resulting in a layout of the A27 and the A4, in which the A4 has an stretch of road of 10 kilometres, without an on- or off-ramp. Since the upstream on-ramp is the only limitation of the total combined length of the DDLSs, this maximum has been chosen. In MOTUS this length can be easily be adapted, but a differentiation in this total length has been left out of the simulation, for simplicity and time related reasons.

4.4.3. Fixed demand pattern

In order to execute an active platoon formation strategy as suggested in the previous chapter, a traffic jam is required to occur. The occurrence of a traffic jam is a combination of the main motorway demand and the on-ramp demand, both are determined by a vehicle generator at the beginning of each lane in the network. The demand on the main motorway is fixed and determined in such a way that it mimics near congested conditions on the Dutch motorway network (by preliminary tests, see appendix D).

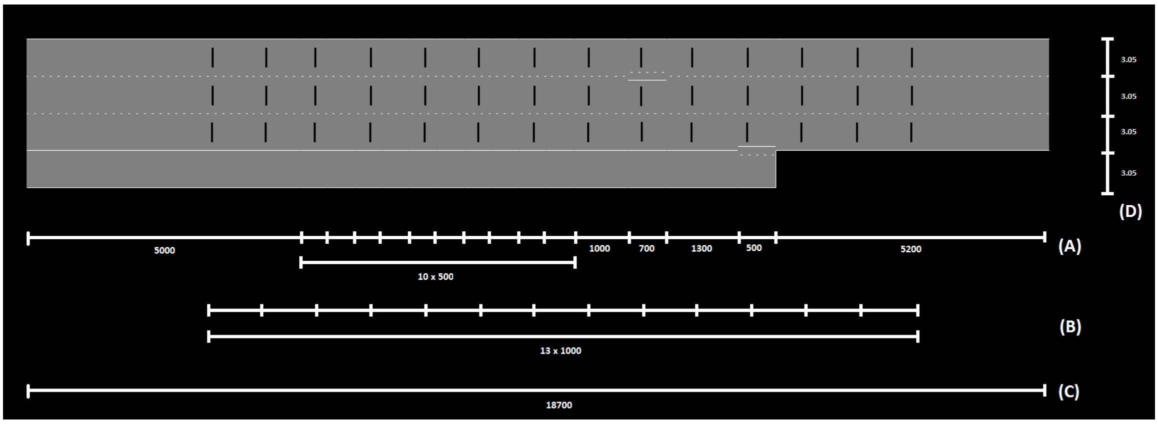

Figure 4.1. – Drawing with all the road layout measurements, group (A) divides the road sections, group (B) shows the distance between the detectors, group (C) shows total length and group (D) shows the lateral distance between the lanes.

This is also done for the on-ramp demand. The peak moment in the traffic jam (with a 30 minute duration), the preliminary tests determined that the on-ramp demand should be 1100 vehicles per hour. In appendix D, these test are presented. The tests were done on two different demand levels, namely 900[19] and 1100. When the tests were done, it showed that even 900 vehicles per hour would not be enough to guarantee a traffic jam. Therefore the peak hour demand on the on-ramp is determined at 1100 vehicles per hour.

In order to create a bottleneck in MOTUS, the following demand pattern has been used:

Table 4.1. – Demand patterns per period per lane (id).

Demand per period [s]	**Demand t1= 0-1200**	**Demand t2= 1200-3000**	**Demand t3= 3000-4200**	**Demand t4= 4200-4800**
Left lane (1)	1500	2250	1500	1000
Middle lane (2)	1500	2050	1500	1000
Right lane (3)	1500	1850	1500	1000
On-ramp (49)	500	**1100**	500	250

4.5. Validation of the simulation

As said by Sargent (2009), *"Simulation models are approximate imitations of real-world systems and they never exactly imitate the real-world system. Due to that, a model should be verified and validated to the degree needed for the models intended purpose or application."*. To compare the results of the two strategies to control strategy with "no" active platoon

[19]Earlier (undocumented) test already showed that at least 900 vehicles per hour were necessary to create a traffic jam.

formation strategy, the data resulting from the simulation of this control strategy must be validated. Only the control strategy with the scenario of 0% CAVs can be validated because the strategies are new and the CAVs do not roam the motorway (yet). This means there is no empirical evidence to compare with the strategies or the scenarios with CAVs. To validate the model, two steps were taken; first the elements that build up the simulation model were checked on validity (if these are invalid, the model itself is invalid), secondly the data and traffic characteristics are compared to real-life observations and already validated traffic conditions.

First, the literature explains that the IDM+ and LMRS model have both been validated (Kesting et al., 2010; Schakel et al., 2012) and the implemented CACC model is valid according to Van Maarseveen (2017). Secondly, the fundamental traffic characteristics of the simulation in this study are validated. The main traffic characteristics of the simulation runs were compared with empirical evidence on motorway traffic. The main characteristics for validation represent: the flow contour plots, the fundamental diagrams, the capacity drop and the shockwave propagation speed. Moreover the amount of deleted vehicles were also taken into account, too many deleted vehicles would challenge the validity of the model. The elaboration of the validation according to the four well known traffic characteristics of congestion and the amount of deleted vehicles in the simulation experiment is presented in appendix E. The performance of the model was deemed valid.

4.6. Expectations of the simulation experiment

In this hypothesis the expectations of the is research are stated per KPI, as they were described in section 4.2.

Average platoon size:
It is expected that both strategies will be able to actively form platoons on the motorway, in congested conditions more efficiently than without a strategy. In general the strategies should generate larger and more platoons than with "no" strategy. For the distinction between both strategies it is expected that the strategy with an one-time density threshold check will generate larger platoons, because of the nature of that strategy. With this strategy all the predecessor DDLSs stay active until the upstream DDLS is deactivated. This enables larger platoons to form.

Outflow:
In the perfect scenario it is expected that the outflow will enhance because of the increase of formed CAV platoons. These platoons can follow each other more closely (a fixed time gap of 0.7 seconds is used). However, this is the first active platoon formation strategy and due to imperfections in the simulation model the results can be less positive than expected. Nonetheless, an increase in traffic flow downstream of the bottleneck is expected, but in short intervals only, caused by the platoons with short inter-vehicle time gaps.

Due to the fact that the strategies are developed to prevent an increase in capacity drop (the deterioration of outflow), the capacity drop is not expected to increase. The length of the designated jam area has been made long enough, that at the end of each strategy the traffic jam is still present. This should be seen in the results (no increase in capacity drop).Furthermore, when the penetration rate of the CAVs increases, the total throughput should be higher. This is due to the low inter-vehicle time gap (0.7 seconds) between CAVs.

Total time spent in the system (TTSiS):
More disturbances are expected due to the active platoon formation strategies, this is the main reason why this experiment is done. It is hard to believe that once a lane has been shut down, this would not influence the total time spent in the system (TTSiS). At least the non-CAVs should be disadvantaged by the strategies. Both strategies are expected to negatively influence the TTSiS. Comparing both DDLSs activation strategies, the DDLSs remain active during the strategy with an one-time density threshold check, therefore this strategy should have a more negative effect on the TTSiS than the permanent strategy. Besides this argument, it can still go one of two ways with the strategy with a permanent density threshold check:

1. The TTSiS can also be worse than the strategy with the one-time density threshold check, caused by the amount of disturbances, i.e. more deactivation and (re-)activations of the DDLSs.
2. The TTSiS is better because the dynamic aspects is coordinated with the traffic jam (density), the traffic is periodically allowed more space when the DDLSs are deactivated for a short period of time. This is the reverse of the argument stated above; the one-time density threshold check remains active leaving larger gaps (increasing its TTSiS).

As a closing statement, it could occur that the **total** time spent in the system is not affected by the strategies. This could occur due to the designated jam area, i.e. the same traffic jam with a fixed bottleneck is present in all scenarios (fixed demand pattern).

DDLSs active time:
The time the strategy is active, is expected to be short. The strategy would only be active during congestion on the DDLSs. Since a demand pattern is chosen with only half an hour of peak intensity, the DDLSs active time is be shorter than this period. Therefore the DDLSs active time could not be more than 37.5% of the time that the vehicles drive on the DDLSs (the simulation runs for 1 hour and 20 minutes).

Deleted vehicles:
It is expected that the amount of deleted vehicles is not larger than the base scenario ("no" activation strategy). This is because the strategy was developed this way. A key aspect of developing a new strategy was to ensure its validity to the maximum. The amount of deleted vehicles could easily be checked during the development, therefore a speed limit was given to the CAVs while the DDLSs were active for the strategy with a permanent density threshold check. This ensured a lower safer speed, that prevented collisions between the CAVs on the dedicated lane and the conventional vehicles that were allowed to go back to the left lane (when the density got below the threshold of 35 vehicles per kilometre).

In general, the simulation results:
This is the first active platoon formation strategy with the use of dynamic dedicated lanes, therefore the results of the experiment are expected to be less positive than described above. However, if the results are as described before, effort should be made to perfect the strategy. If the strategies perform above expectation, the developed strategy should be recommended to be used for the initial deployment of the CAVs. When the disadvantages outweigh the advantages of the strategies, the strategies should be discouraged for real-world implementation.

To enable real-world implementation, safety has to be considered (or at least mentioned) during the alternation of activation and deactivation of the DDLSs (with the permanent threshold activation strategy). For both strategies safety could be an issue, because the preliminary tests showed that the traffic jam propagates backward quicker. This could also be a cause for the expected TTSiS deterioration.

Besides the safety issues, this hypothesis gives an expectation of the optimal scenario considering the different penetration rates. Because the strategies have been developed with the purpose of aiding the initial deployment of the CAVs, the low CAV penetration rate scenarios (2% and 5%) are expected to improve the most compared to the base scenario.

4.7. Conclusion

In this chapter three different types of variables are distinguished. This resulted in the performance per scenario, given a fixed network environment with fixed vehicle properties. The results are presented in the next chapter (5), also all of the results are given in tables in the appendices H, I and J. The performance of the strategies compared to the base scenario ("no" strategy) is presented per KPI.

5. Results and discussion

The simulation experiment described in chapter 4 produced results that are analysed and require further discussion. This chapter does two things: in section 5.1 the results are analysed and section 5.2 discusses these results. The results show the data, per KPI, that the experiment produced it also presents a short analysis of the results, mentioning the interesting characteristics. The discussion will be the interpretation of the results. It will explain the effects the strategies have on the traffic condition. This includes remarks and suggestions (improvements) on these strategies, the simulation model and the simulation experiment. Concluding with a discussion that includes the advantages, disadvantages and the limitations of the experiment. The observations will be used in the conclusions and recommendations of the last chapter (chapter 6). In this chapter a conclusion of the research is drawn and the recommendations for further research and the motorway authority is given.

5.1. The results analysis

The results are presented according to the five relevant KPIs:

1. An indication of average platoon size [number of CAVs]. This is done by presenting the number of CAVs that drive directly in front of the specific CAV. This specific CAV is following the

2. Outflow [vehicles/hour], (out of and) downstream of the bottleneck.

3. Total time spent in the system (TTSiS) [seconds], meant to show the deterioration of the traffic jam. This KPI also makes a distinction between TTSiS of CAVs and non-CAVs.

4. DDLSs active time [%], percentage of time the DDLSs are active and switched "on".

5. Amount of deleted vehicles [number of vehicles], as a indication of comfort, safety and validity.

These KPIs are tested on all strategies including the control/base scenario strategy (also referred to as: "no" strategy). The exact numbers that belong to the results of the indicators (KPIs) above, are located in the appendix; appendix H represents the result of KPI number 2 (outflow), appendix I represents the result of KPI number 3 (TTSiS) and the results of the other three KPIs (average platoon size indication, DDLS active time, deleted vehicles) are stated in appendix J. The TTSiS (and outflow) is divided in: all vehicles, CAV only and non-CAVs only. This is to show the effect of the strategies on the different type of vehicles. Furthermore, appendix K depicts results in more summarized figures showing all scenarios' speed contours, strategy active time plots and bar plots of platoon size indicators.

The results are first given in the sections below, after which a short analysis follows that mentions the interesting characteristics of the results. The results represent the average of the six different runs of the simulation model (The simulation is done with six different seeds, see appendix D). An estimate was made to ensure that, with 95% confidence, the average of each run lies no further than 3% of the mean. Below stands the results per KPI, including the three different strategies (including to "no" strategy) and with seven different scenarios considering the CAV penetration levels.

5.1.1. Average platoon size indication

First off, as can be seen by a representation of the traffic conditions below, the screen shots from the GUI (in MOTUS) show that numerous platoons have been formed with both platoon formation strategies (10 percent CAV penetration rate). This clear representation of the platoon formation (not random) indicates a promising result. The differences of the strategies can also be seen, figure 5.1 shows the dedication stays active with no conventional vehicle cut-ins. On the other hand figure 5.2 shows that the strategy permanently checks the density threshold, clear conventional vehicle cut-ins are visible, meaning that the density went below the threshold of 35 vehicles in a lane section.

Strategy with an one-time density threshold check:

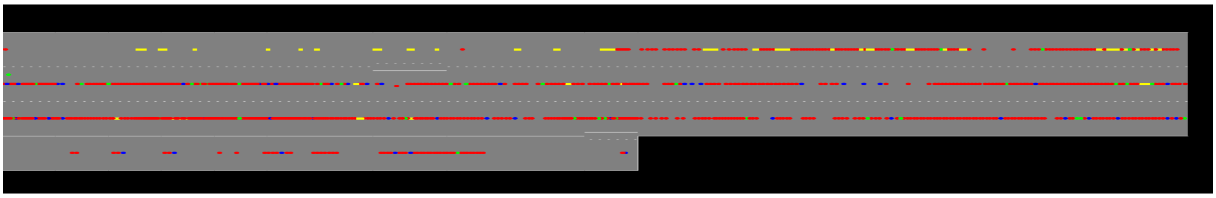

Figure 5.1. – MOTUS‘ vehicle class representation: zoomed in version at the end of the strategy, showing multiple platoons created by the strategy with a one-time density check.

Strategy with a permanent density threshold check:

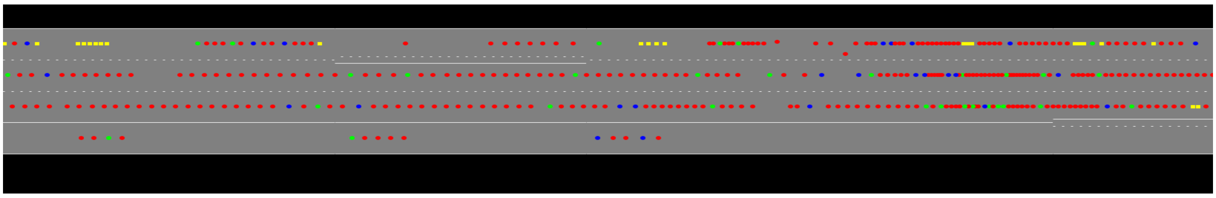

Figure 5.2. – MOTUS‘ vehicle class representation: zoomed in version at the end of the strategy, showing multiple platoons created by the strategy with a permanent density check.

In order to quantify the results of platoon formation, the purpose of this research, the results of the experiment are shown in a table J.1 in the appendix (J) which presents the weighed average of the platoon size per per scenario (per CAV penetration rate). This is the average between the size of the platoons weighed over the number of platoons formed (including the CAVs that drive alone, in a platoon of 1). This is an indication of the average platoon size, done by counting the amount of CAVs that a following CAV has (directly) in front of him. Below, in figure 5.3 the results are bundled in a bar plot.

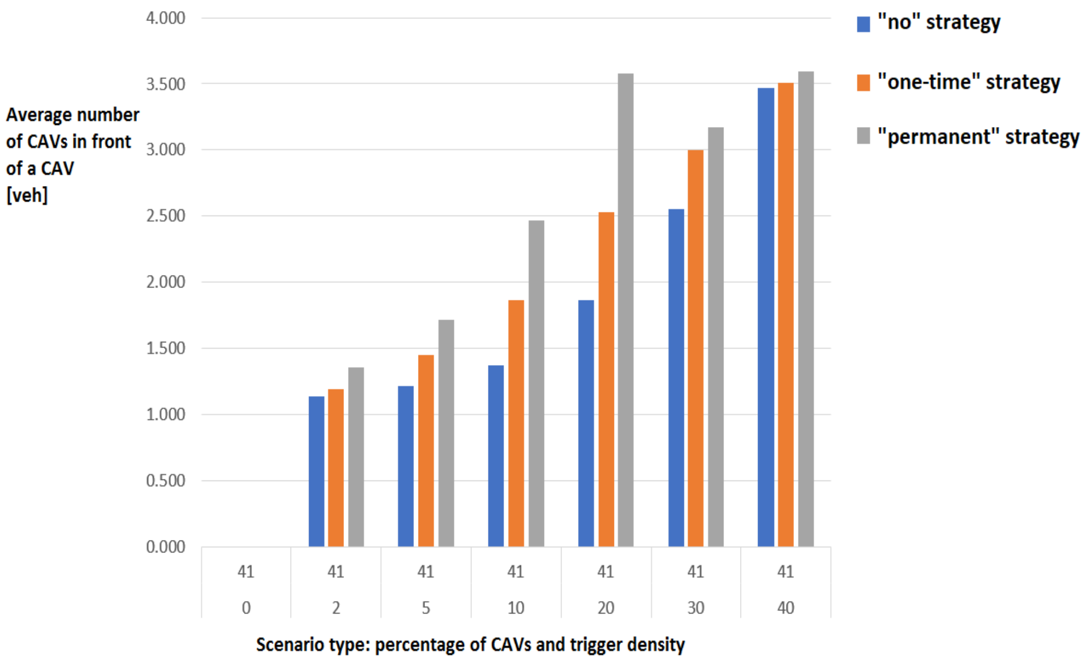

Figure 5.3. – An indication of average platoon size, with the weighed average (size of platoon over number of platoons) amount of CAVs directly preceding a particular CAV per penetration level scenario.

It can be seen that both activation strategies outperform the "no" strategy. Especially the DDLS activation strategy with a **permanent** density threshold check (grey bar) outperforms the "no" strategy, the 10% and the 20% scenario outperform the "no" strategy by an average number of leading CAVs of respectively 1.1 and 1.7 CAVs. Also in the DDLS activation strategy with an **one-time** density threshold check (blue bar) outperforms the "No" scenario, but it does so by lesser margins.

There are two typical scenarios depicted in figure 5.4 and 5.5, these are the scenarios of 10 and 20 percent CAVs. A result that stands out is the column of 0 (zero) preceding CAVs. This indicates that there are no preceding CAVs, it does not necessarily mean that they are the leader of a platoon [20]. Therefore the surplus of vehicles in the "zero (0) CAVs in front" column, in regards to the "one (1) CAV in front" column, **represent the CAVs that drive alone.**

This surplus number is larger for the control scenario ("no" strategy) in regard to the DDLS activation strategy with an **one-time** density threshold check (green middle bar), the control strategy has 75 more lone driving CAVs. For the DDLS activation strategy with a **permanent** density threshold check (yellow left bar), the control strategy has a surplus of 150 CAVs more that drive on their own.

[20]This would only be the case if there are just as many CAVs in the column of "1 preceding CAVs". Than all the CAVs in the "0 (zero) CAVs in front" column would drive in front of the CAVs in the "1 (one) CAV in front) column.

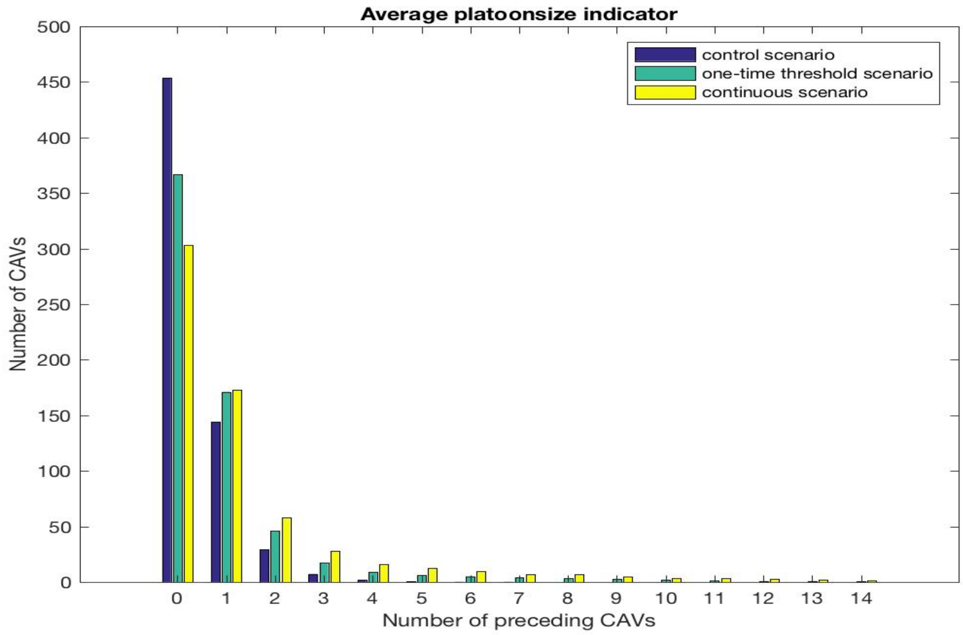

Figure 5.4. – An indication of platoon size, for each strategy at 10% CAV penetration.

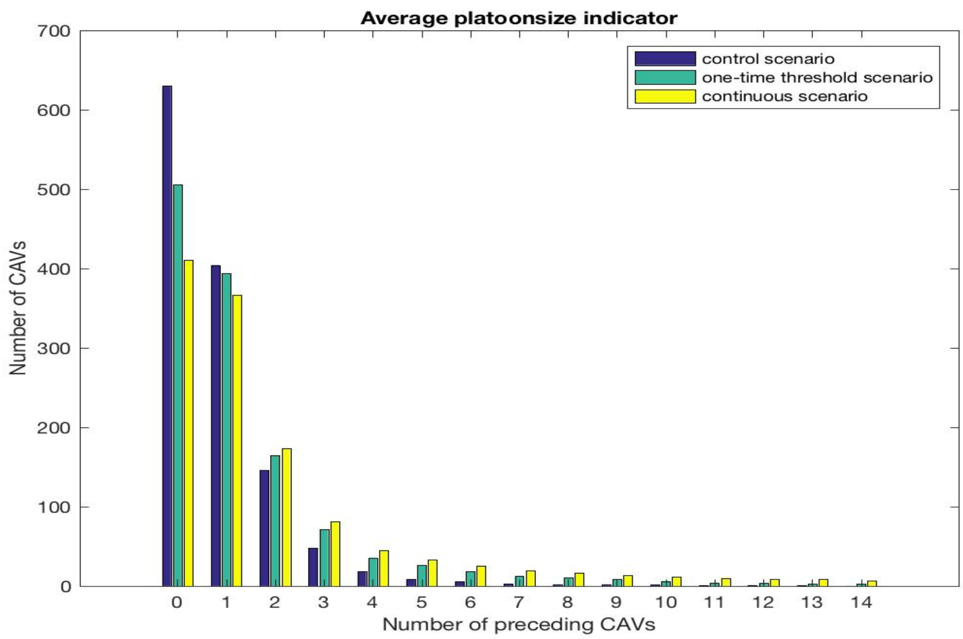

Figure 5.5. – An indication of platoon size, for each strategy at 20% CAV penetration.

5.1.2. Outflow

Appendix H, table H.1, shows the outflow of all strategies for all seven scenarios. The total outflow of all vehicles compared with the CAV penetration level is presented in figure 5.6. Figure 5.7 presents the outflow of only CAVs.

In general, the outflow of all strategies increases if the CAV penetration levels goes up. In the results presented below we see the mean values of the six runs (or seeds as explained in appendix D.1) presented. It appears that the scenario with 0 percent CAVs is favourable for the dedicated lane activation strategies, however, these differences fall well into the 95% confidence interval as shown in appendix M. It **is** odd that the dedicated lane activation strategies, seem to perform better or equal the control strategy, but that will be analysed in the discussion.

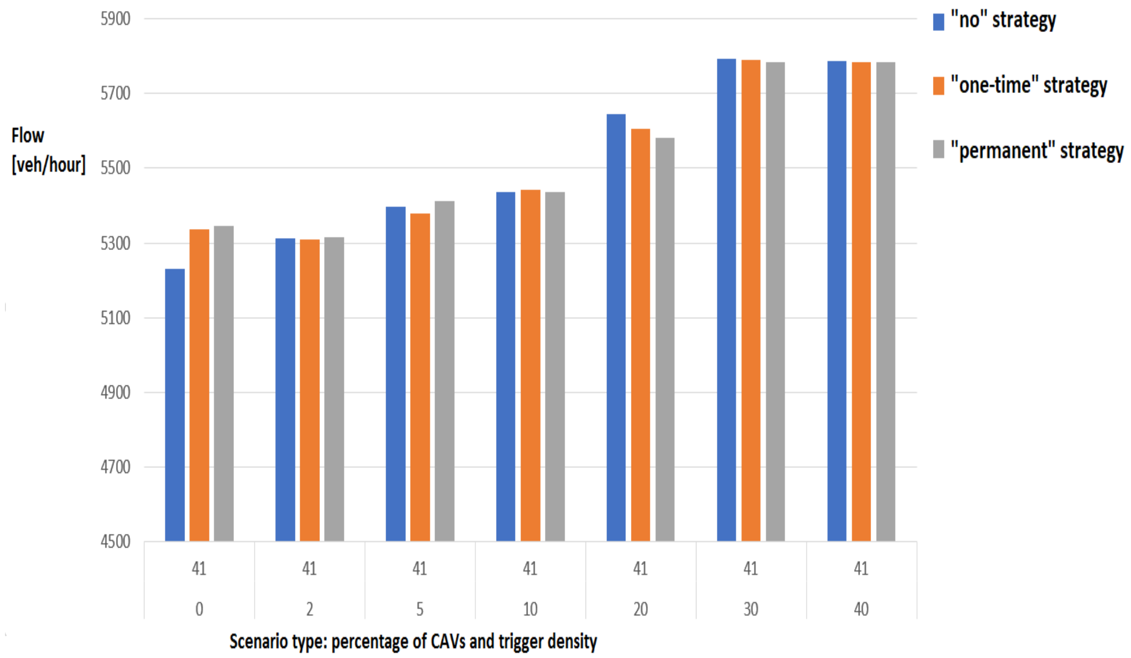

Figure 5.6. – Outflow [veh/h] after the bottleneck, for all vehicles.

By analysing the CAV-only outflow, in figure 5.7, it can be seen that the outflow of the CAVs is (nearly) the same for all strategies. A simple deduction by subtracting the CAVs from the total outflow would logically imply that the outflow of the conventional vehicles would also be the same.

An interesting result is the flow contour plot of figure 5.9 and 5.10 that show the flow contour plots of the two strategies with DDLS activation with the scenario of 10% CAVs. This is done because of the abnormal shape of this contour plot at this scenario. What can be seen here is the gap between the two jams waves in comparison to a solid stable jam in figure 5.8 (the base scenario with "no" strategy). This suggest possible dangerous dynamical lane dedication behaviour which will further be discussed in the discussion.

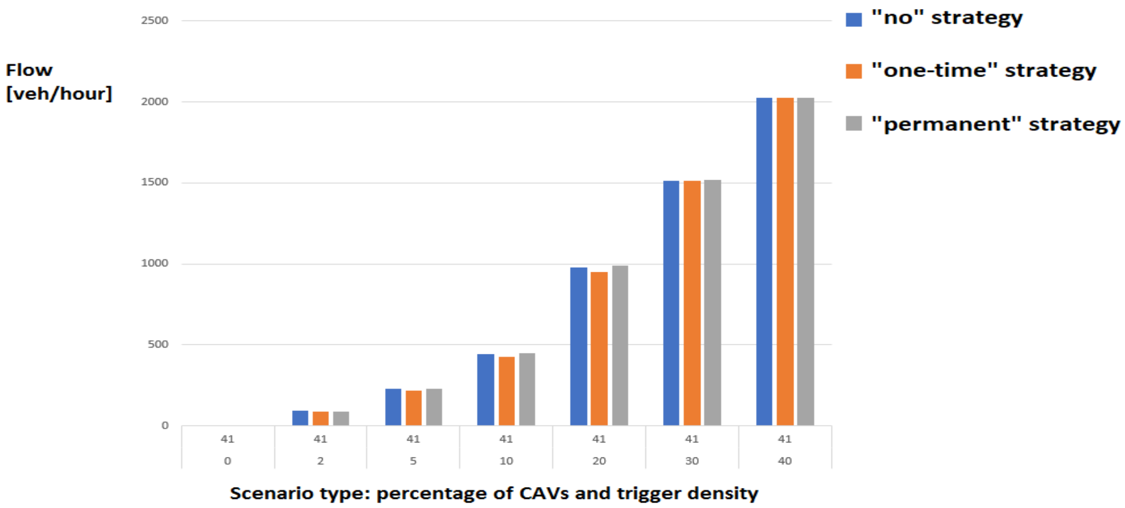

Figure 5.7. – Outflow [veh/h] after the bottleneck, for CAVS-only.

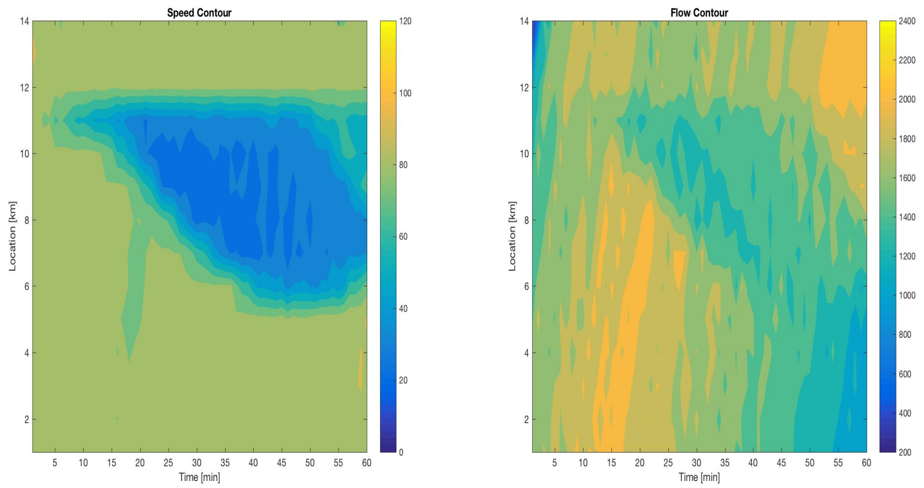

Figure 5.8. – Speed/flow contour plots for the scenario of a CAV penetration rate of 10%, "no" strategy.

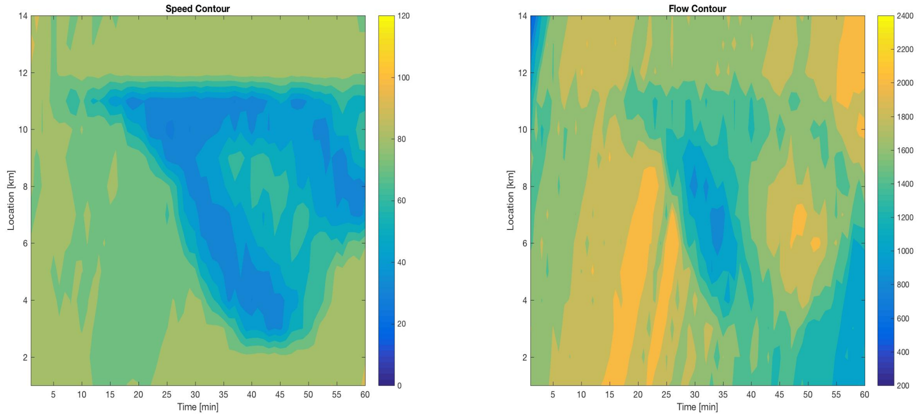

Figure 5.9. – Speed/flow contour plots for the scenario with a CAV penetration rate of 10%, DDLS activation strategy with a "one-time density threshold check".

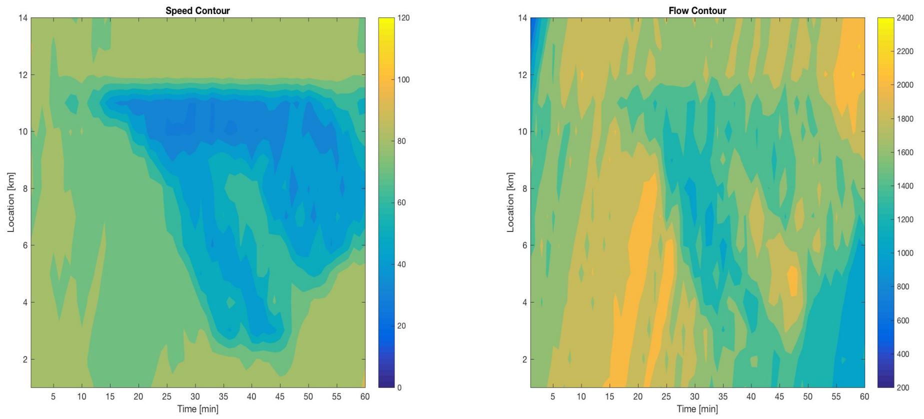

Figure 5.10. – Speed/flow contour plots for the scenario with a CAV penetration rate of 10%, DDLS activation strategy with a permanent density threshold check

5.1.3. Total time spent in the system (TTSiS)

The third KPI result is the TTSiS, this indicates the total time spent by all vehicles in the system (in seconds). In appendix I, table I.1 shows the results in numbers of the TTSiS for all the strategies and all the scenarios. This indicator should show the level of disruption in the system.

Figure 5.11 shows the TTSiS for all vehicles, the differences between the DDLS activation strategies and the control strategy ("no" strategy) is shown in figure 5.12. It can be seen that the TTSiS is larger for every strategy, except for strategy 2 with 2% CAVs. However, if the 95% confidence interval is checked (appendix M) the 95% lower bound value of "no" strategy is 6631073 seconds and the 95% upper bound value of the permanent strategy is

6645714. This indicates that this difference is not statistically significant, thus, statistically, they are the same value. However, the difference at 20% CAVs is statistically significant. The difference, at most, is 50.000 seconds for the strategy with an one-time density threshold check and 64.000 seconds for the strategy with a permanent density threshold check. Respectively on average per car (6700 cars) this is a delay of 7.4 seconds and 9.5 seconds.

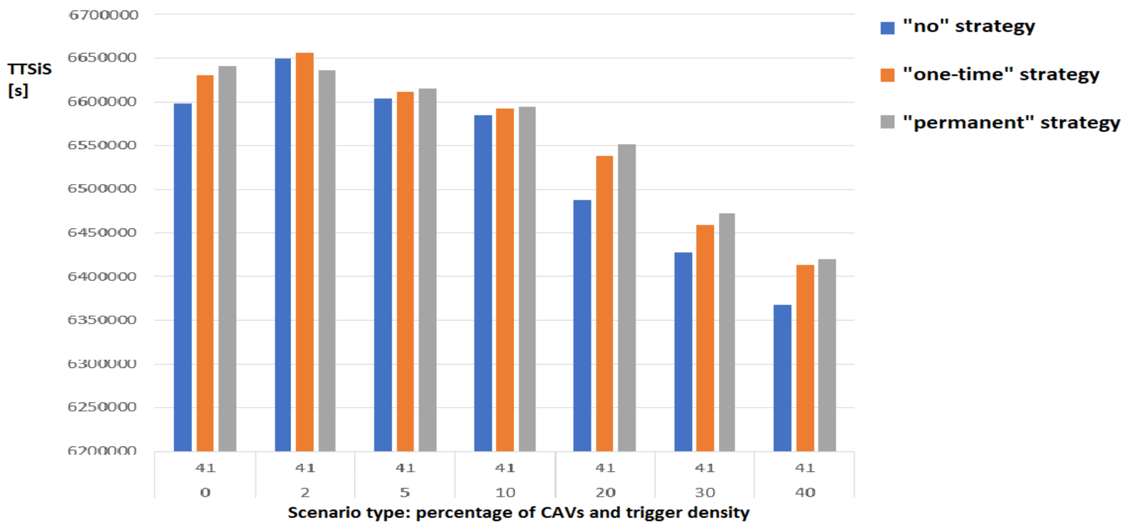

Figure 5.11. – TTSiS of all vehicles

Besides the difference between all vehicles, a separation between vehicle types has been made[21]. The comparison of the strategies and the control strategy is differentiated by vehicle type and is shown in figure 5.13. This figure shows the total time spent in the system per vehicle type, i.e. CAVs and conventional vehicles. Indicating the effect of the strategies per vehicle type. When comparing the strategies with the control ("no") strategy, it is seen that all CAVs receive a total time advantage and the conventional vehicles receive a (larger) total time disadvantage. The size of the delay is comparable with no distinction in vehicle type as seen in figure 5.12 (on average 12.7 seconds of delay for non-CAVs).

An important remark on this result is necessary due to the nature of the data of the bar plots (figures 5.11, 5.12 and 5.13). The TTSiS bar plots include every vehicle(!), this includes the vehicles in free flow before and after the congestion. However, the vehicles affected by the strategies are only the vehicles in the congestion (that is how the strategy works). Therefore the results shown by figure 5.12 and figure 5.13 are too positive. This distinction is made in figure 5.15 where the time spent in the system (TSiS) per vehicle is shown. This difference results in a difference of 200 seconds between the mean of the CAVs and the mean of the non-CAVs (the red and black dots in figure 5.15). This is a difference of 3 minutes and 20 seconds instead of 12 seconds as the results in the TTSiS shows. This is elaborated in the discussion.

[21] The plot of the TTSiS per vehicle type are placed in appendix I (figures I.2 and I.3), since a difference in these plots is hardly visible.

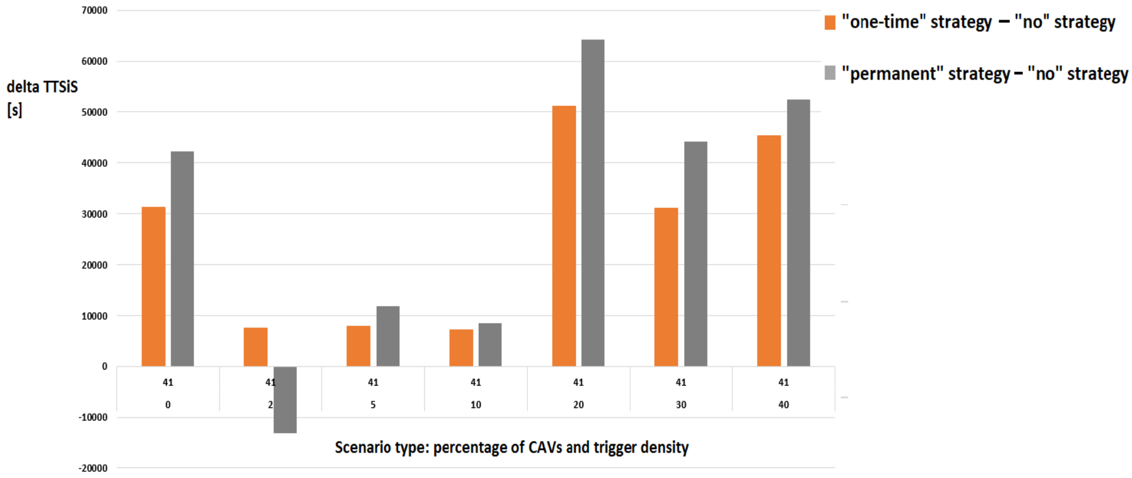

Figure 5.12. – TTSiS difference between strategies and the control scenario ("no" strategy).

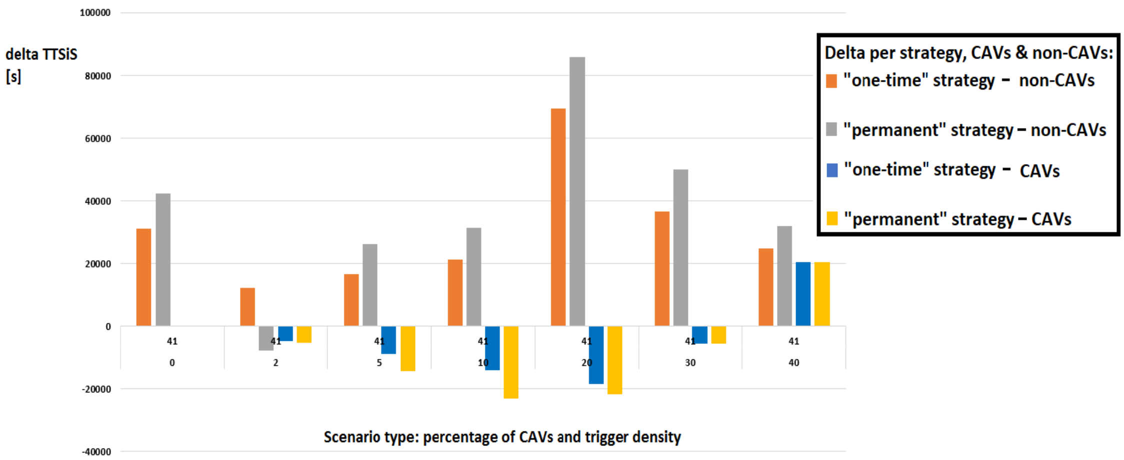

Figure 5.13. – TTSiS delta‘s between the strategies and the control scenario ("no" strategy) differentiated by vehicle type (CAV and non-CAV). Positive means that vehicle type spent more time in the system with the strategy, negative means that vehicle type spent less time in the system with that strategy.

Figure 5.14 explains the layout of figure 5.15, where the three different strategies are compared. The figures visualised the time spent in the system **(TSIS)** per vehicle type (CAV and non-CAVs). This is done for 10% CAVs and a platoon formation strategy with a permanent density threshold check. For a list of all the scenarios, see appendix K.3.

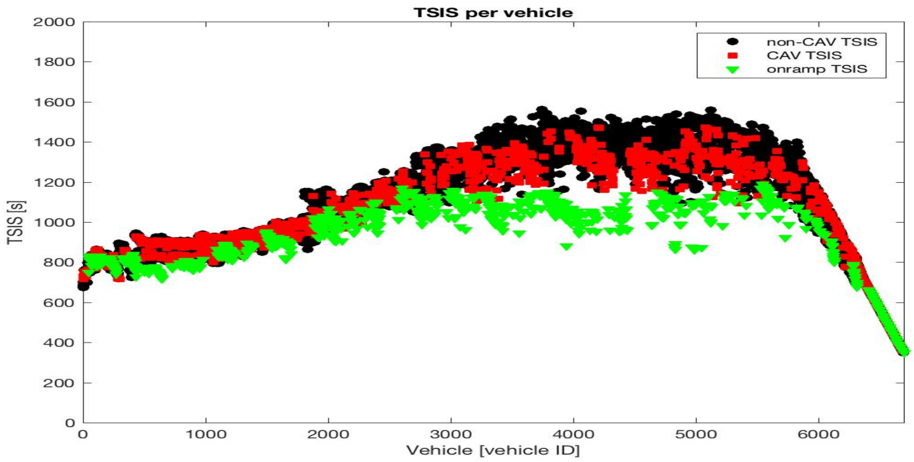

Figure 5.14. – The time spent in the system (TSiS) per vehicle. On the y-axis the time spent [s] is given. The x-axis describes vehicle ID. The black dots represent non-CAVs, the red squares represent CAVs and the green triangles represent the on-ramp vehicles.

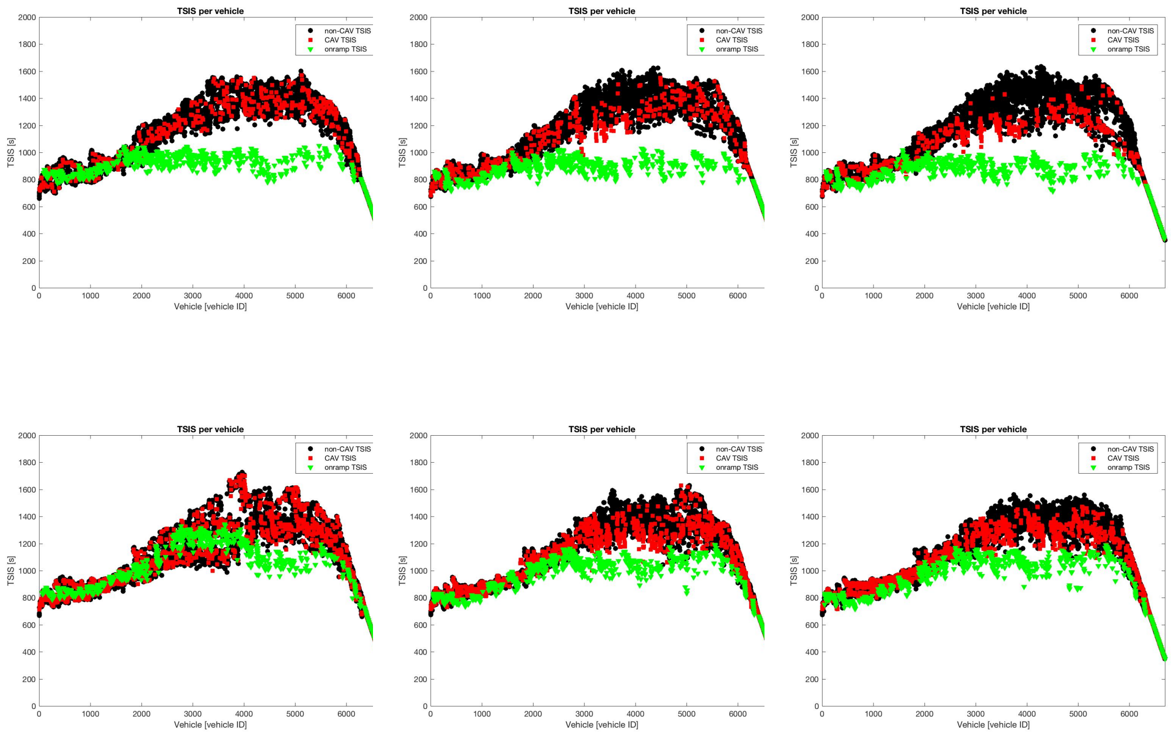

Figure 5.15. – The individual vehicle time spent in the system of 10% (top) and 20% (bottom) CAVs. The left figure shows the base scenario ("no"strategy), the middle figure shows the strategy with an one-time density threshold check and the right figure shows the strategy with a permanent density threshold check.

5.1.4. Percentage the strategy is "ON"

In this section the percentage the system is active is presented. This KPI exist because it can explains the effectiveness of the strategy and it can show whether or not the strategies behave how they should (how they are programmed). The percentage of "switched-on" time is calculated by dividing: the time the switched-on CAVs spent on the DDLSs, by the time all the CAVs spent on the DDLSs (see equation 5.1).

$$\%"ON" = \frac{Time - spent - by - "switched - on" - CAVs - in - DDL - sections}{Time - spent - by - all - CAVs - in - DDL - sections} \quad (5.1)$$

According to formula 5.1 the percentage of "ON"-time, with 0% CAVs for both strategies should be zero. However this is not the case, it still functions without the CAVs present. In the real world this would not be the case, but in this simulation all of the vehicles are modelled with a density threshold check (the non-CAVs as well).

Figure 5.16 shows that the activation strategy with a permanent density threshold is "on" at least twice as long as the other DDLS activation strategy for the scenarios of 2% to 20% CAV penetration. This difference disappears at 30% CAVs. A simple observation notices that from 30 percent onwards, the strategy is nearly non-active, there is almost no congestion (appendix K.1 indicates this clearly). This is due to the fact that the CAVs improve traffic throughput at higher CAV penetration rates (which corresponds with the findings of van Arem et al. (2006)).

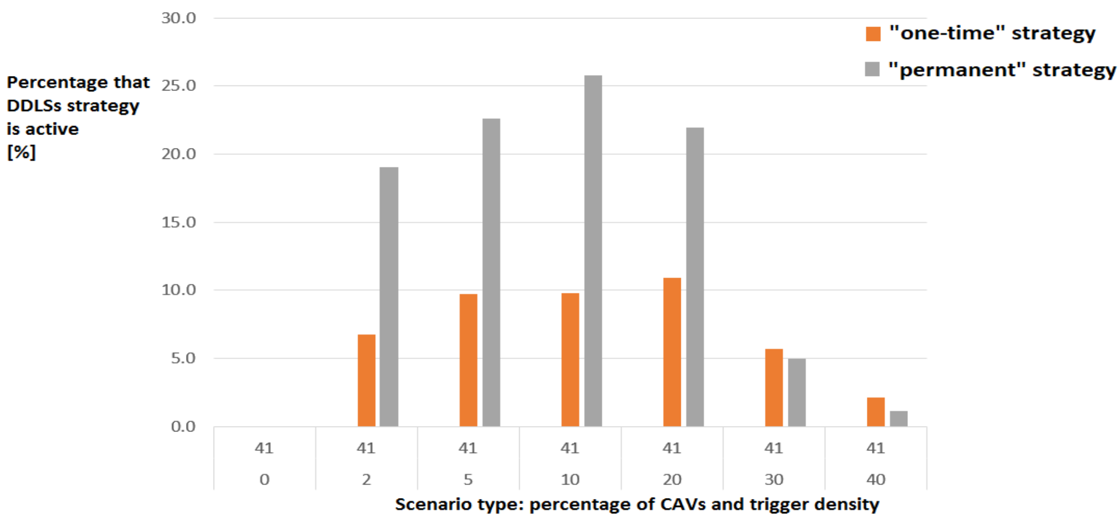

Figure 5.16. – Relative percentage the relevant strategy was turned "ON". With the percentage of "ON" time on the y-axis and scenario type (percentage CAVs and trigger density) on the x-axis. "0% is assumed to be equal to 2% CAV penetration rate"

Also added to the results is the "on-switch" detection plot over location and time shown in figure 5.17 and figure 5.18. These figures give an indication of the time a CAV is switched on over space. Both figures also explain the different strategies. Figure 5.18 shows that the dedication switches "off" in the middle of the strategy indicating that figure 5.18 represents the activation strategy with a permanent density threshold check. In appendix K.2 all of the results (of one run/seed only) of all scenarios are given. This gives a great overview of the activation (and deactivation) process of both strategies.

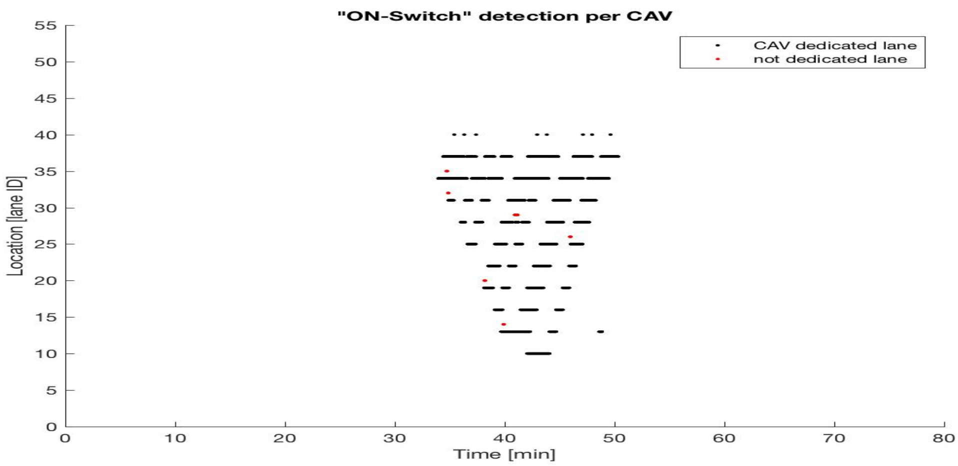

Figure 5.17. – The "On-switch" detection plot over location and time. Considering the DDLS activation strategy with an one-time density threshold check with 2% CAVs.

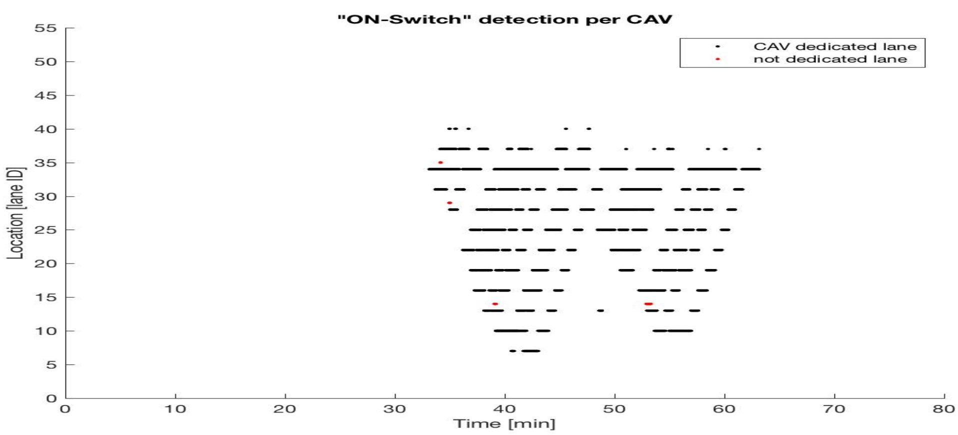

Figure 5.18. – The "On-switch" detection plot over location and time. Considering the DDLS activation strategy with a permanent density threshold check with 2% CAVs.

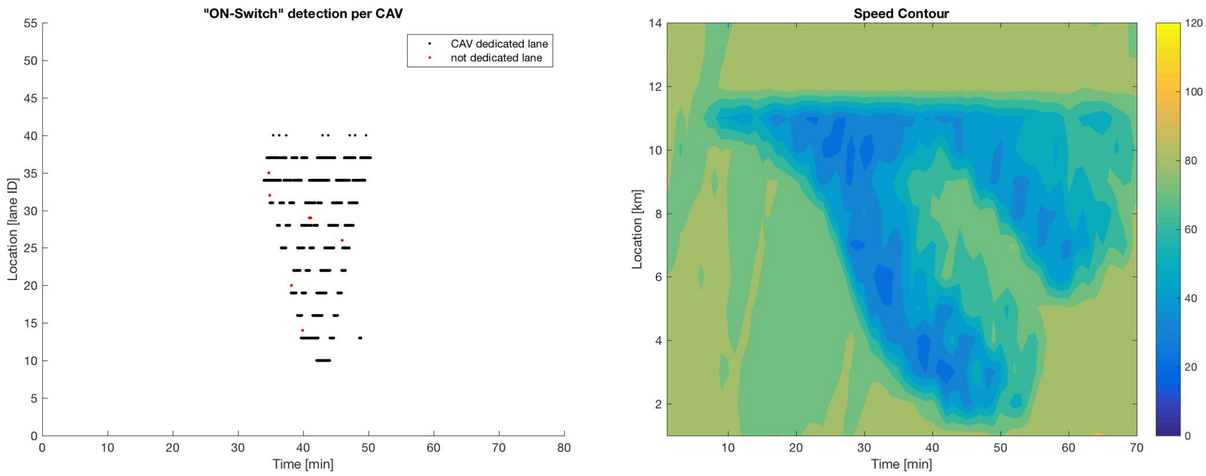

Figure 5.19. – The "on-switch" detection plot (left) compared to the speed contour (right), for the strategy with an one-time density threshold check and with 2% CAVs. Both describe location and time.

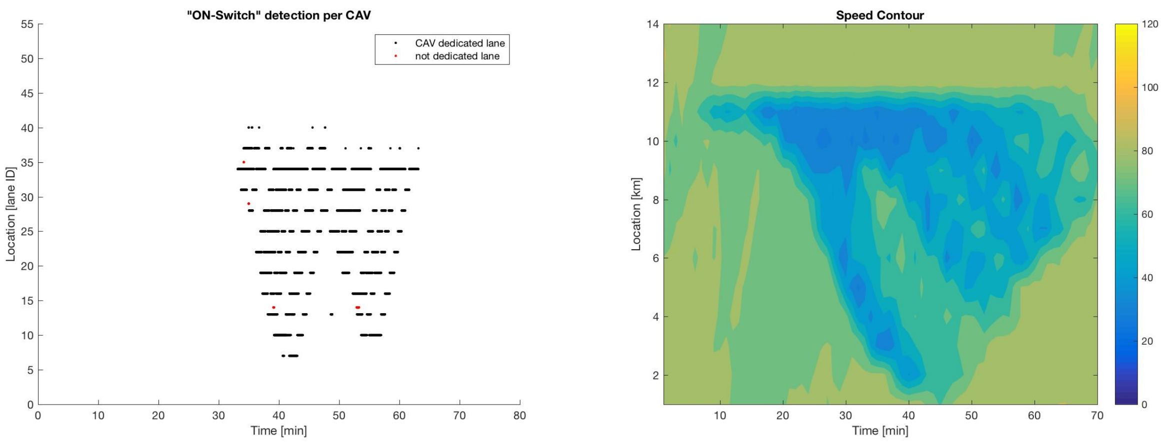

Figure 5.20. – The "on-switch" detection plot (left) compared to the speed contour (right), for the strategy with a permanent density threshold check and with 2% CAVs. Both describe location and time.

It can be seen that the activation (and deactivation) process of the strategy works as it should. Figure 5.19 and 5.20 are created to compare figure 5.17 and 5.18 to the speed contour plots of the same scenarios. The following observations on the operations of the strategies can be made:

- The strategies turns "on", when a traffic jam occurs at the downstream DDLS.
- The strategies turn "off", when the traffic jam reaches the final DDLS (most upstream DDLS).

- The strategies turn of gradually, like explained in section 3.7
- The behaviour that belongs to the exemption that exists for the platoon formation strategy with a permanent density threshold check (as explained in section 3.4.3) is present. This can be seen by the bottom of the on-switch detection plot, it is turned of as soon as the density drops (below 35 vehicles per hour).

As said before, all of the "on-switch" detection plots of the relevant scenarios are presented in appendix K.2 when this is combined with all of the speed contour flows presented in appendix K.1 the proper functioning of both strategies is shown. Also, this appendix (K.2) gives an indication of the time one strategy is "on" compared to the other.

5.1.5. Deleted vehicles.

The deleted vehicles are presented in the figure below (figure 5.21), the base scenario and the two strategies present nearly the same values of deleted vehicles. However, there is a significant difference detected at the penetration rate of 30%. The mean of the deleted vehicle differs 13 vehicles from the control scenario. However, the total amount of deleted vehicles is less than 1% for all scenarios. An increase of 13 deleted vehicles is an increase of (just) 0.2% of the total amount of vehicles deleted.

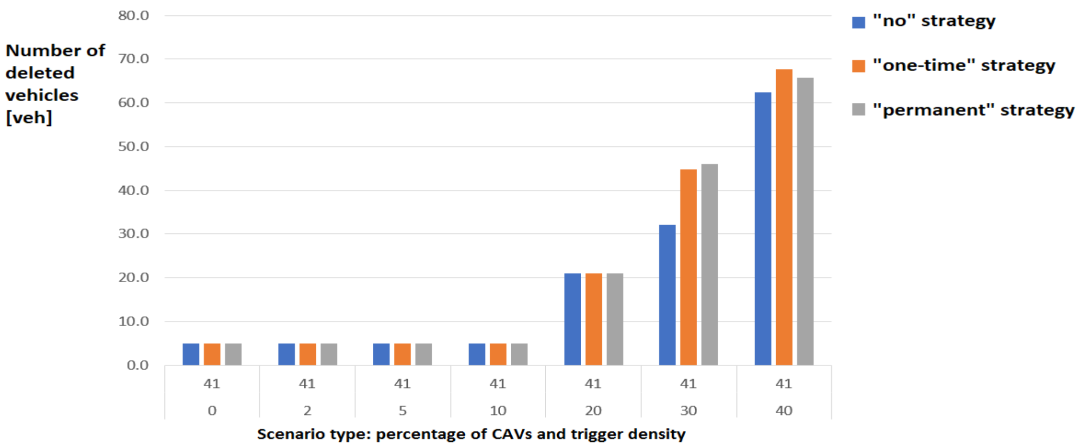

Figure 5.21. – Deleted vehicles per strategy per penetration rate. Caused by vehicles that were unable to leave the on-ramp and merge on the main motorway.

5.2. Discussion

An important section of the report, the discussion. This section answers the question, *"What do the results mean?"*. To answer this, the discussion consists of three parts. This discussion starts with a structured summation of the interpretations of the observed results per KPI, it does so in the list below. After this summation a cross-check between the interpretations of different KPIs is done in order to explain the effects that occurred and to check if the strategy works properly. The effects are then compared with the hypothesis from the previous chapter (section 4.6), extracting the results that will lead to the conclusion on whether or not the strategies are a success. This conclusion is left for the next chapter chapter (6). Lastly the limitations of these results are mentioned.

1. **An indication of average platoon size:**
   - The visualization according to figure 5.1 and 5.2 display that platoons are formed in a **not** random manner.
   - Figure 5.3 and table J.1 support that platoons have been formed in a more effective way.
   - The bar plots, shown by figure 5.4 and 5.5 illustrate that there are more lone driving CAVs in the control strategy ("no" strategy). Thus, the platoon formation strategies are effective in making platoons.
2. **Outflow, downstream of the bottleneck:**
   - The outflow for each scenario of CAV penetration rate was as expected; The outflow increased if the penetration rate increased. Due to the increase of CAVs the platoons are more easily formed, there are simply more possibilities, these platoons maintain low inter-vehicle time gaps increasing the throughput.
   - Also expected was the (statistically) insignificant difference at 0% CAVs for the strategies compared to the control strategy. This was also the case for all other scenarios, but it seems remarkable at 0% CAVs. However, due to the fact that the designated jam area was **designed** to maintain the capacity drop (no further deterioration), this result was actually as expected. It seems as if this part of the goal to **"not"** let the traffic conditions deteriorate was achieved.
3. **TTSiS:**
   - Initially it appears that the difference between the control strategy and the DDLS activation strategies is non-existent (maximum of 12 seconds per vehicle), as seen in figures 5.11, 5.12 and 5.13 with respectively the TTSiS of all vehicles, the differences between the strategies and the differences per vehicle type and the strategies. However, when the comparison of TSiS per vehicle and vehicle type is shown (figure 5.15) it can be seen that the CAVs have an obvious advantage. The differences of the TTSiS take into account the free flow traffic before and after the congestion and this traffic is not influenced by the strategies. Figure 5.15 makes it clear that the individual CAV in the traffic jam wins around 200 seconds (3 minutes and 20 seconds).

- The other remarkable result is that the non-CAVs were hardly affected by the strategies (at least not statistically significant). This could be due to the design of the strategies as explained below in subsection 5.2.1.

4. **DDLSs active time:**
   - At most the activation strategy with a permanent density threshold check was on 26 percent of the time.
   - At most the activation strategy with an one-time density threshold check was on 11 percent of the time.
   - The nature of the strategy with a permanent density threshold check is the reason why the strategy is active for a longer period of time. This strategy tries to fill the dedicated lanes during the time it is activated, ensuring that the off-switch threshold of the last DDLS is reached at a later moment time.

5. **Amount of deleted vehicles:**
   - There was a scenario (30%) with a significant difference in numbers, but this was only 13 vehicles on a total of 6700 vehicles. This number went up due to the increase in CAVs that have to merge to get on the main motorway. The overall result on the deleted vehicles was satisfying and small enough to keep the model valid.
   - After the simulation run analysis it was clear that the deleted vehicles all resulted from the merging behaviour. The on-ramp demand was designed to induce a traffic jam, therefore the demand pattern of the on-ramp was chosen to be very high. This high demand is the cause of the deleted vehicles. The on-ramp demand only has a traffic jam generation function, therefore the deleted vehicles are not considered a negative effect of the strategies.

This list represented the facts and an analysis based on the facts. The interpretations of the results per KPI are combined and a qualitative analysis strategies is performed. This presents advantages and disadvantages for both strategies and is done in section 5.2.1 below.

5.2.1. Verdict by a qualitative analysis

In this qualitative analysis the interpretations (and sometimes also straight up results) from the list above are combined, giving a full analysis of the results of the strategies. This overview separates the positive and negative aspects of the strategies according to the advantages and disadvantages that are attached to each strategy.

Advantages:
To strategies perform well, this is seen by looking at the average platoon size indicator, the outflow and the DDLS active time. These present beneficial aspects of the strategies.

First and foremost platoons *are* formed actively as shown by the **platoon size indicator**, meaning more CAVs were able to be part of a platoon. The DDLS activation strategy with an one-time density threshold check, is only active (at most) only 10% of the time increasing the value of the platoon size indicator by almost 40%(at most). The DDLS activation strategy with a permanent density threshold check is active at most 26% of the time and this strategy increases weighed average of the platoon size indicator by more than 100% (at most)."

Secondly the platoon formation strategies work as they were meant to. This becomes clear when the **"on-switch" detection plots** are compared with the speed contour plots (see section 5.1.4[22]), all the main characteristics of the strategies were present. These are:

- The "on" switch that responds to congestion at the first DDLS.
- The "off" switch that responds to congestion at the last DDLS.
- The gradual switch off sequence in the downstream direction.
- The exception of the strategy with a permanent density threshold check showing intermediate deactivation of the strategy.

Furthermore, the **outflow** results showed that the designated jam area performs properly, preventing an increase in capacity drop.

Disadvantages:
The disadvantages of the strategies are related to the KPIs of (out)flow [vehicles/hour] and TTSiS [s]. The outflow (or actually flow over the network) of the strategies showed the speed contour plots of all scenarios (also see appendix K.1). The speed contour plots for the strategies showed shockwaves that propagated backwards, this was not the case for the control ("no") strategy. This disadvantage indicates discomfort (frequent braking) and safety issues.

At first the TTSiS did not seem affected by the strategies, but once the vehicle type distinction was made, seen in figure 5.15, the difference became clear. The strategies caused a disadvantage of 200 seconds for the conventional vehicles, on a journey of 1600 seconds. While this disadvantage is not that large on it‘s own, the drivers of the conventional vehicles may disagree with that fact in the actual traffic jam[23].

5.2.2. Expectations vs. simulations

The expectations (section 4.6 are compared with the simulation results. This is done according to a division by three different categories: *1.* The expectations that were right, *2.* the expectations that were wrong and *3.* Results that were striking.

Expectations that were right:
The platoon formation expectations were right, this strategy actively formed platoons that were larger than the control strategy. Also the different nature of the two strategies was predicted; the permanent density threshold strategy would allow more vehicles to go in between the CAV platoons. The platoon formations and the different platoon sizes per strategy are clearly shown the figures 5.1 and 5.2.

[22] All result plots are shown in appendix K
[23] This could cause unwanted "cutting-in-line" behaviour

Furthermore, the expectation that the strategies would not have an increased (or decreased) capacity drop came true. The gaps that were created during the activity of the strategy were solved by the traffic jam that was present at the designated jam area. Also the strategy were active only (at most) 26% of the time, which is well below the estimated absolute maximum of 37.5%.

Expectations that were wrong:
The one-time threshold activation strategy did not have an higher outflow than the control strategy nor did the strategy with a permanent density threshold check. All the outflow results were all statistically the same, the differences were not significant. The strategy with a permanent density threshold delivered larger platoons, this was unexpected because the strategy with a permanent density threshold check allowed cut-ins by conventional vehicles.

Furthermore, It was expected that the scenarios with 2% and 5% CAVs were the most effective, this was not the case. If figure 5.3 and figure 5.16 are compared it can be seen that the scenarios of 10% and 20% CAVs are active a similar amount of time, but those scenarios do have a larger increase with the platoon size indicator compared to the base scenario.

Results that were striking:
The extra delay according to the TTSiS for the strategies with zero percent CAVs was less than with two percent CAVs. This is probably due to the ACC behaviour of the CAVs; If the CAVs are the leader of the platoon or when they are driving on their own, their time gap to the predecessor is 1.5 seconds instead of 0.7 seconds (when they follow another CAV). Therefore, the scenario with 2% CAVs has the highest TTSiS for the control ("no") strategy.

With 0% CAVs another remarkable result is found. The outflow (figure 5.6) is the same for the DDLS activation strategies as it is for "no" DDLS strategy[24]. This shows that the designated jam area did its work. A possible reason for this performance is that the development of the platoon formation strategies took place in MOTUS, the same environment as where the simulation runs were done. That way the goals could be achieved by fighting the symptoms during development, instead of theoretically working the problem. This pitfall is also mentioned in the limitations (section 5.2.3). There is also a small chance that the strategies have an accidental "COSCAL""-like (Mahajan et al., 2015) or "ramp metering"-like (Hegyi et al., 2005) effect. Where the temporal dedication causes a controlled restricted inflow, further research should be done to understand more about the traffic dynamics during the strategies.

5.2.3. Limitations of the results

However good the results may be, there are limitations that need to be discussed. These limitations need to be considered in order to get the full picture. The limitations consider: *1.* The lack of congestion with 30% and 40% CAVs, *2.* the traffic conditions regarding safety, *3.* the proper use of MOTUS, *4.* the (lack of) validation of the CAV model in MOTUS, *5.*

[24] The strategy in the simulation model MOTUS, works for every vehicle including non-CAVs. Therefore, with 0% CAVs the conventional vehicles are still forbidden to use the left lane.

the human driving behaviour and the lack of focus of this research on the following model. The elaboration of these limitations is stated below:

1. **Lack of congestion with 30% and 40% CAVs:** In this discussion the results of the scenarios of 30% and 40% CAVs are primarily **not** taken into account. The results of these scenarios explain that the demand pattern was not sufficient enough to ensure congestion (as explained in the results). A recommendation is that the demand pattern should be increased according to the CAV penetration rate.

2. **The traffic conditions regarding safety:** In early developments of the simulation, there were a lot of collisions present in the model, due to the quick lane changes caused by the DDLSs activation. These were removed by restricting speed during the activation. However, one more safety issue remained, the propagation speed of the tail of the traffic jam increased with the DDLSs activation. No collisions on the motorway were present, but the increased propagation speed (as can be seen by figure 5.9 & figure 5.10) could be dangerous. The problem is that this research has no indication of how dangerous this is. i.e. it has no "distance-to-collision" (or "time-to-collision") indicator.

3. **Designed to perfection in MOTUS and tested in MOTUS:** The previous item presents us the limitation of the validity of the model. The results are very positive due to the fact that the development of the strategy was aimed to resolve these negative effects. The prototyping of the strategies was done in MOTUS, whilst the same model also conducts the simulation experiments. Therefore all the unwanted behaviour could be "tweaked" out (by tuning) in advance, until every setting was perfect. Although the goal of "no deterioration of traffic conditions" is met this way, the set-up might be too perfect for real world implementation or occurrence.

4. **Validation on the CAV model:** MOTUS is validated and calibrated for a model with only conventional vehicles, this simulation contained CAVs (CACC vehicles) in mixed traffic. The simulation (MOTUS) is not validated to have a CAV model on the network, this should be done with empirical data, but because of the lack of CAVs this is very hard to do.

5. **The human driving behaviour:** Another limitation of the model is that human driver behaviour. With the LMRS lane change model implemented the drivers only consider other vehicles that are directly in front or behind them. A normal human driver can anticipate far further than this, for example courtesy lane changes by that are performed to let someone merge onto the motorway. The same thought can be made with regard to CAV platoons. If a CAV platoon was formed and this was indicated properly it is not hard to imagine that a human driver would leave the platoon alone and NOT merge right in front of it deteriorating traffic throughput[25]. This happened a lot in the model, which disturbs the platoons (and thus the results).

6. **Lack of longitudinal focus:** The focus of the research was entirely on the lane changing needed when the DDLSs were activated. Due to the lack of time, this focus

[25] A simple assumption is made here, the driver could know about this deterioration, because of the proper government advertising campaign that instructed him

had to be made. The following model made by Van Maarseveen (2017) had been adopted, this longitudinal model was made for the purpose of on-the-fly platooning. Given time this model could have been improved, e.g. making sure the CAVs in a platoon would not yield for other vehicles or improve the platoon formation in the longitudinal direction which would increase the platoon formation efficiency.

The limitations end the discussion. In section 6.2 this discussion will be used as a guideline to recommend the reader on the findings and possibilities of this research. The recommendations are made to improve the model and the strategies, but reduce the limitations.

6.Conclusions and recommendations

The experiment results have been analysed and a conclusion is presented, followed by some recommendations on the results of this research. The conclusion answers all the research questions stated in section 1.3. It does so by a short conclusion according to the findings in the previous chapters. The recommendation is focussed at further research, but it also presents recommendations for use by the road manager (RWS). The recommendations for the road manager include practicalities describing future work to make the active platoon formation strategy ready for the Dutch motorways.

6.1. Conclusions

This research is done to develop an active platoon formation strategy for CAVs in congested and mixed traffic. Also, the active platoon formation had to take place on the motorway. A simulation experiment was performed to register the effects of the developed strategies on the traffic conditions. Therefore, this conclusion starts with the answer of an unambiguous question: "Are the developed strategies successful?"

The answer to that question is: "Yes, for the most part". There are several limitations, uncertainties and assumptions that make the positive results vulnerable. However, the scope of the research and the recommendations do take these liabilities in consideration. When you leave out the limitations of the simulation model and disregard the fact that some assumptions are ambitious (e.g. no data transfer lag), the results as defined per KPI are (very) positive.

Average platoon size:
The indication of the average platoon size, indicated that both strategies actively formed platoons more efficiently than "no" strategy. Between the strategies the DDLS activation strategy with a permanent density threshold check outperformed the DDLS activation strategy with an one-time density threshold check (figure 5.3, section 5.1.1). The strategies outperformed the control ("no") strategy the most at the scenarios of 10% and 20% CAVs.

Developed strategy, 5 characteristics:
The combination of the speed contour plots with the "on-switch" detection plots showed that the four main aspects of the strategies worked according to the design, namely:

1. The "on" switch that responds to congestion at the first DDLS.
2. The "off" switch that responds to congestion at the last DDLS.
3. The gradual switch off sequence in the downstream direction.
4. The exception of the strategy with a permanent density threshold check showing intermediate deactivation of the strategy.

Furthermore, the outflow results showed that the designated jam area performs properly, it prevented an increase in capacity drop.

Some disadvantages:
However, there are two disadvantages: *1.* During the activation period the conventional vehicles have a delay of 3 minutes and 20 seconds compared to the CAVs. This could trigger disobedience by the human drivers. They could find it unfair that CAVs have such an advantage (although it is only 3 minutes), disregarding the lane dedication. In the worst case scenario this could cause unsafe driving behaviour (e.g. sudden lane changes, variable speeds in the dedicated lane, etcetera). Safety (and discomfort) is also a concern, indicated by the speed contour plots that showed stop and go waves at both strategies.

This conclusion was build up by the answers given to the research questions stated in section 1.3. Each chapter tried to answer the related research questions, the conclusions per chapter are stated below.

6.1.1. The literature review and strategy description

Since it became clear that no other platoon formation strategies presented a strategy to let CAVs platoon in congestion alongside other conventional vehicles (**on** the motorway), a strategy of sorts had to be developed to reach the objective of this research.

The literature review found a solution direction in two layers of the hierarchical control layer structure (Shladover, 2005). In these layers, aspects of congestion and the use of a dedicated lane were found viable solutions. These solution directions were adopted and worked out in chapter 3; "The platoon formation strategy". This was done with the method of prototyping, by using the objective and elements of the scope as the requirements to come to a design for a platoon formation strategy.

The developed platoon formation strategy involved the use of state of the art knowledge on existing platooning strategies (1.) and the knowledge of traffic and demand management solutions (2.);

1. The close following capabilities of the CAVs and the existing active & passive platoon formation strategies.
2. The implementation of dynamical dedicated lanes (that can be switched "on" and "off" when congestion sets in) and certain properties of congestion which are essential for the CAVs to deal with and use in the new developed strategy.

The exact processes that occur in the strategy is clearly explained in section 3.4. Finally the strategy was developed and tested in MOTUS (Schakel et al., 2013; TUDelft, 2015) which is argued to be the best simulation model for this research (section 2.7).

The developed strategy is innovative and could be the foundation on which other active platoon formation strategies can be build in the future. The following reasons explain why, in no particular order:

- It is an active platoon formation strategy, where platoon formation occurs **on** the motorway and in congestion, this is the first in its kind.

- It could benefit throughput downstream of the bottleneck (because CAV platoons increase throughput).
- As soon as the first CAVs roam the motorway, this strategy can be implemented. It is not necessary to wait for an increase in CAV penetration rates, before this platoon formation strategy can be implemented.
- This strategy does not need large infrastructural interventions.
- The infrastructure and CAV vehicles work together, but the strategy is fully focussed on the infrastructural part of the collaboration. Therefore any other CAV control algorithms can be implemented in this strategy.

6.1.2. The simulation experiment

The effects of the active platoon formation strategies is tested by a simulation experiment. This simulation experiment introduced five dependent variables or key performance indicators, namely: *1.* Average platoon size [#CAVs], *2.* Outflow (after the bottleneck) [vehicles/hour], *3.* Total time spent in the system (TTSIS) [seconds], *4.* DDLSs active time [% of total time] and *5.* Amount of deleted vehicles [#vehicles]. The conclusion of the results of the simulation experiment and the discussion thereafter is presented below.

6.1.3. The results and discussion

This subsection is an extension to the introduction of the conclusion (section6.1), the concluding results were already mentioned there. This subsection concludes on those results, according to the two different strategies. A short conclusion of the discussion is also given.

The permanent strategy showed great promise having up to 100% more CAVs in a platoon (see figure 5.3 and table J.1), for the scenario of 20% CAVs. For both strategies, the scenario with 10% CAVs also performed very well. There was a smaller difference in average platoon size compared to the control strategy, but the increase in TTSiS was minimal. More results are presented in appendix K, giving an overview of all scenarios and strategies with the concerning traffic condition plots.

The discussion presented an in-depth analysis of the results, starting with a summation and analysis of the results. Then the advantages and disadvantages of the strategies mentioned, which are used to compare the simulation results with the hypothesis (section 4.6). The results were determined as very positive, having some disadvantages, but nothing that could not be mitigated or solved. The recommendations in the next section (6.2) are based on this discussion, primarily on the last section of the discussion "the limitations of the results" (section 5.2.3).

6.2. Recommendations

The recommendations in this section are divided in a practical and a theoretical part. The practical part describes recommendations to the road manager (Rijkswaterstaat); what can this institution take away from this research and how can Rijkswaterstaat contribute to further research. The same goes for the the theoretical side[26], what can be updated in the model and what further research is necessary. Ultimately a final recommendation is made.

6.2.1. For the road manager

In these recommendations the road manager is primarily asked for contributions towards this research. How they can make sure these strategies can be implemented.

For the use of the dynamic dedicated lane sections (DDLSs) the technological information infrastructure above the roads need to be in order. In other words the matrix signs need to be able to dictate the (mandatory) lane changes. Also the sign "CAV-only" on the matrix signs above the road should be determined. A sensitive human factor process, therefore Rijkswaterstaat has a department specialized in human factors. However, a proposal has been made in appendix L.

To further validate the developed strategies, empirical data needs to be generated. This can be done by on-road tests and measurements. Two scenarios could be looked into in order to empirically support this research:

Scenario 1. Shut down the left lane in congestion that has a fixed bottleneck. This will capture the human behaviour as well as their acceptance of this implementation. This will also monitor the behaviour of the traffic conditions. **To compare these on-road tests, this thesis include a scenario with 0% CAVs for both DDLS activation strategies while still activating the DDLSs.** This could validate the research, but new findings or the entire negation of this research could also occur. Safety has to be ensured for this empirical experiment (e.g. by first testing in a closed environment).

Scenario 2. Undertake more CAV experiments on the motorway, similar to the tests on the A58 (beterbenutten.nl, 2017). This will help validate the CACC/CAV model for the simulation in MOTUS. This is difficult because CACC vehicles are not widely available and enough observations need to be made (for a proper validation).

A suggestion for testing the strategies, this research suggest to start testing with the DDLS activation strategy with an one-time density threshold check. This is the most safe option, it is constant and will not constantly change the DDLSs activation. *Scenario 1* can validate the results of this strategy more easily, because the lane sections are kept dedicated/closed (instead of changing this constantly).

Furthermore, to increase the effectiveness of the platoon formation strategies strategies,

[26] particularly focussed on the T&P and automotive department of the TU Delft

the human behaviour and CAVs need to be adjusted. In order to let this strategy work in the future, five suggestions are made:

1. Information campaigns should be started. Where human drivers are told what to do when they encounter a CAV and when they encounter a platoon of CAVs.

2. The CAVs should be made recognisable, that way a human driver can recognise a CAV or a platoon of CAVs. This can be done by an orange bar light on top of the CAV.

3. Install (and allow) in-car devices that can detect when a platoon of CAVs is near the human driver. Which would prevent conventional vehicle cut-ins of the CAV platoons. This would also allow the CAV to detect the non-CAVs, increasing the ability of the CAV to see and anticipate.

4. To ensure the dedicated lanes are really dedicated, human drivers should be penalized for driving into an active dedicated lane.

5. To increase the responsiveness and (thus) safety of the strategies, the drivers (of non-CAVs) have to be made aware of the presence of a DDLS area. A clear sign should indicate that CAVs are active in this area and that drivers should be aware of CAVs and their specific signalling.

Overall Rijkswaterstaat should prepare for the "age of the CAVs", however it does have time to prepare. The strategies showed promising platoon formation results and even if these specific strategies will never be implemented, the suggestions are still valid. Most of the suggestions recommend a legislation change; Allowing CAVs to drive on the public roads, CAV identification signalling lights, CAV responsibility issues (maybe an issue for the manufacturer), conventional vehicle identification for V2V (and V2I) communication, etcetera. In particular the road authorities (RWS) should make it easier to perform tests with CAVs on the motorway, in order to validate the simulation models. Although it may take a while before CAVs are mass produced and legally allowed on the motorway (due to possible bureaucracy) it is wise to have the scripts ready when the "age of the CAVs" is upon us.

6.2.2. For the researchers

The recommendations for the researchers are split into two subjects, strategy improvements and further research. Strategy improvements speaks for itself, further research is about the alteration of the experiment by addressing different topics or approaches that are not present in this research. These extensions to the topic presented potential and could be considered as added value for the research field.

Improvements of the strategies
The strategies could be improved by implementing one or multiple of the following adjustments and recommendations:

- Building a central controller for MOTUS implementation.

- Increasing the sensitivity of the strategies in the model.

- COSCAL (v2) implementations on the strategy.
- V2I communication for increase efficiency
- Improving the longitudinal CAV model.

The topics in this list are elaborated below.

The implementation of the strategies in MOTUS goes according to the control of each individual vehicle, i.e. the vehicle decides whether or not the density threshold is met and acts accordingly (changes lane or not). However, it is preferred that a centralized controller controls the lane sections, this would be similar to the real-world implementation. Besides the fact that this is more realistic, with a central controller alterations of the strategies are easier to implement. This would increases the flexibility of the strategies, allowing them to be applicable on more scenarios (i.e. other CAV penetration rates, other types of bottlenecks etcetera).

Increasing (or decreasing) the sensitivity of the strategies would allow strategies to cope with more than the given scenarios. This model improvement is explained according to the suggestions in the list below.

- Both DDLSs activation and deactivation strategies can be refined, making sure the lane changes will go more smoothly in terms of abruptness of the lane changes that occur now. (Now they need to do the lane change as soon as possible, no exceptions, due to the controller inside the vehicle).
- The switch "on" density could be altered per scenario, if the controller knows that the designated jam area remains filled up, it could allow a designated jam area of *only* 1 kilometre.
- The trigger density could be adjusted real time, in order to switch the DDLSs "on" or "off". This could allow conventional vehicles to decrease the gap behind the CAV platoons, preventing a possible occurrence of capacity drop.
- Other bottlenecks could be used. With a wide moving jam this would mean that the deactivation might take place at the front of the jam. (an unsure idea, but with a central controller this can be implemented.)

Altering the sensitivity, means that the model can cope with more than one traffic condition. Essentially this means that the strategies can be enhanced with more properties. Adding rules and conditions that allow the strategies to cope with more and different scenarios (i.e. less demand, more demand, less CAVs more CAVs, other traffic conditions, etcetera).

The CAVs can be enhanced with V2I communication. This way the CAVs could announce to the centralized controller that many (or few) CAVs are in the vicinity of the DDLSs area. When the centralized controller knows that there are no CAVs in the area, it would not activate the strategies. If the controller knows many CAVs are on their way, it could activate the strategies sooner (less strict pre-conditions).

The strategies might especially be enhanced with the incorporation of the traffic management strategy COSCAL (V2) (Mahajan et al., 2015). This would work as follows: While the DDLS activation strategies are active, COSCAL (V2) will reduce the inflow into the DDLSs area. This would decrease the propagation speed of the jam upstream into this area. In turn this makes the strategy safer, it could make it last longer and straight after the deactivation of the strategy any traffic jam would also be solved. Whether or not this works, has to be researched. This complex alteration could only work with a centralized control system for the strategy implementation in in MOTUS.

Also the longitudinal control of the CAVs has to be updated. Once again this should be controlled by a centralized controller. This controller would direct the CAV leader of a future platoon to drive slower and the followers to drive faster, until they caught up. The CAV capabilities in the model are not able to do this properly for these strategies. With an empty lane, this improvement should be very feasible.

Further research

From the possible improvements, this second part of describes further research possibilities. To start with the development of different strategies. The developed strategies in this research are first of its kind, new active platoon formation strategies are encouraged to be researched. Other platoon formation strategies could implement a centralized controller (as mentioned before), could implement other CAV models, could be implemented with another type of bottleneck (e.g. wide moving jam or moving head bottleneck) or it could make another lane the dedicated lane (e.g. the middle lane or the right lane).

Besides other strategies, another network with a different cause of the fixed bottleneck can also be researched. In the first phases of this research a lane drop was suggested as the fixed bottleneck. This idea was abandoned because of time constraints, but is seemed very promising[27]. The lane drop scenario has a huge advantage; the lane drop would occur anyway, if the CAVs are held up in the last section the lane drop would only occur sooner. As said above, with a lane drop the CAVs could be held up in the last section of the lane drop, when a platoon is complete they could be let go onto the main road. This is expected to be very effective, with minimal disadvantages to the traffic conditions.

Last but not least, tests on safety should be performed. Now only deleted vehicles are counted, but a more robust safety indicator should explain more about the safety issues for the strategies.

The scenarios with a CAV penetration rate of 30% and 40% did not have congestion or very minimal congestion. Therefore the strategies did not get activated and the effect of the strategies on these scenarios could not be determined. Further research should include a higher demand pattern to ensure congestion with these scenarios. Also the inflow could be increased per scenario (CAV penetration rate) as much as each scenario increases the throughput see figure 5.6.

[27]Late in this study and after some deeper thought, it appeared that this might be (way) more promising than the on-ramp scenario.

Final recommendation:
This research advices to continue to develop both strategies. First tests on the Dutch motorway are advised to be with the strategy with an one-time density threshold check, because dedicated lane sections do not suddenly deactivate. Testing this strategy first is therefore the safest option. Also it is strongly recommended to perform a real-world test with a fixed bottleneck with a lane drop. But first such a strategy has to be developed and validated in a simulation model. Furthermore, the control system in the simulation model should be changed to a centralized controller, which would increase the efficiency and robustness of the strategies a lot. Further research with different scenarios must be researched to increase the robustness, validity and the feasibility of the strategies. As soon as CAVs are allowed on the Dutch motorway, the platoon formation strategies can be implemented. Therefore, Rijkswaterstaat should have a ready to go script for when the "age of the CAV" is upon us.

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Appendices

Appendix A.SAE levels of automation

The table below according to SAE Committee (2016) shows the different levels of automation standards. From level 0, no automation, to level 5, full automation. In this thesis the level 0 vehicles are the conventional vehicles. The level 1 vehicles are the ACC vehicles and the level 2 vehicles are the CACC vehicles as these vehicles are adopted as the CAVs mentioned in the report.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	No Automation	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver Assistance	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	Conditional Automation	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	High Automation	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	Full Automation	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure A.1. – Different SAE levels of automation.

Appendix B. Parameters of the CAV implemented in the model

Parameters that are implemented by MOTUS to be used in simulation model. These parameters are used for both strategies.

Table B.1. – Vehicle parameters that are implemented in the model

Parameter	**Symbol**	**Value**
Standstill distance [m]	s_0	3
Desired time gap ACC [s]	t_{des}	1.5
Desired time gap CACC [s]	t_{des}	0.7
Control parameter CC	k_v	0.3
Control parameter gap error	k_s	0.18
Control parameter relative speed error	$k_{\Delta v}$	1.93
Collision avoidance switch: on (1), off (0)	k_r	1
Aggressiveness coefficient	Q	20
Perception range coefficient	P	40

Appendix C.

This appendix contains the tables C.1 & C.2 about the advantages and capabilities of different simulation models, according to the research done by Van Maarseveen (2017) on different simulation models. This includes the chosen simulation model for this research; MOTUS, an open-source microscopic traffic simulation package. With the two lists presented here and the requirements for the development of a platoon formation strategy, this simulation model could be argued to be implemented.

C.1. Overview simulation model (dis-)advantages

Platform / characteristics	Advantages	Disadvantages	Special characteristics
VISSIM[1]	• Easily available • Huge flexibility • Unlimited number of vehicle classes can be defined • External driver behaviour can be implemented using DLL plug-in	• Hard to calibrate due to large number of parameters • Overestimates the number of discretionary lane changes • The workings of many functions remain unclear	• Vehicles can display different behaviour at different locations • Thresholds prevent reaction to minor changes
MOTUS[1]	• No black boxes, full understanding of inner workings possible • Relatively simple programming in Java allows adaptation and extension of the model • Allows focusing on specific parts of complex networks during simulation • Relatively realistic car-following and lane change models (with relaxation and synchronization) • Support available at the TU Delft	• Limited graphical user interface • No manuals available • Limited functionality • Especially car-following model still has some drawbacks (no driver reaction time, no thresholds to prevent reaction to minor changes)	• Incorporates OBUs and RSUs that can interact. • Open source
OTS[1]	• Similar to MOTUS, but more complex programming and increased functionality for more accurate results	• Similar to MOTUS, but more programming skills required and increased functionality • Parts still under construction	• Open source
AIMSUN[1]	• No overtaking on on-ramp • Driver heterogeneity in terms of aggressiveness	• Somewhat of a 'black box'	• Both microscopic and mesoscopic modelling • Vehicles can display different behaviour in three different behavioural zones
CORSIM[1]	• Prevents ping-pong effects of lane changes • Desired speed at on-ramp based on adjacent lane speed for smooth merging	• May miss European traffic rules e.g. 'keep right'. • Limited number of driver classes limits heterogeneous behaviour	• Incorporates extra type of lane change: random lane change • 3 second threshold for lane changes
FOSim[1]	• Calibrated for the Netherlands • Designed for motorway corridors • Straightforward user interface • Extensive manual and even a basic course available	• Old core may miss recent insights into lane change behaviour • No heterogeneous driving behaviour • Many parameters are fixed or can hardly be changed • Limited number of driver classes • Location of merging doubtful • Little interaction between lanes	• Vehicles at an on-ramp can always merge if allowed deceleration is set high enough
MITSIMLab[1]	• Open source nature allows full understanding • Extensive GUI	• Meant mainly to evaluate the effects of traffic control measures • Runs on Linux OS • Transition of acceleration behaviour between free flow and car-following not smooth • No cooperative lane changing	• Open source • Can implement traffic control measures
MATLAB applications[1]	• Relatively easy programming • Can easily interact with other programs • Obtain any performance indicator	• Limited functionality of existing simulation codes • No driver reaction time, no thresholds to prevent reaction to minor changes	• Interaction with other programs • Politeness factor per lane change type, acceleration threshold value

Figure C.1. – An overview of the advantages and disadvantages of the different simulation models researched by Van Maarseveen (2017).

C.2. Overview simulation model capabilities

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

Figure C.2. – An overview of all capabilities relevant to this research of the different simulation models researched by Van Maarseveen (2017).

C.3. MOTUS' vehicle speed and longitudinal position

$$v_{i,t+1} = v_{i,t} + a_{i,t}\Delta t \tag{C.1}$$

$$x_{i,t+1} = x_{i,t} + v_{i,t}\Delta t + \frac{1}{2}a_{i,t}\Delta t^2 \tag{C.2}$$

The vehicles' speed & longitudinal position is updated every 0.2 seconds. This is the same as the "lag" from the communication. In these equations, Δt is the time interval for the updates (0.2 s), $a_{i,t}$ is the desired acceleration of vehicle i at time t which is calculated with the controller (CACC or ACC) and $v_{i,t+1}$ & $x_{i,t+1}$ are the speed [m/s] and position [m] of vehicle i at time t+1 (Schakel et al., 2012; TUDelft, 2015).

Appendix D.

It is impossible to come up with the right strategy straight away. Numerous iteration steps were taken before the strategy described above, could find its way to the paper. The preliminary test determined the control variables as the on-ramp demand, the trigger density and the road layout, but it was also used to optimize the model in order to eliminate collisions. This appendix gives an overview of all the tuning iterations (of the strategy) and modifications, a summary of the most important development choices and iteration steps are stated below.

D.1. Amount of simulation runs: amount of seeds

The results of the different simulation scenarios, are a result of the average of different seeds. Each seed exist of a run in MOTUS, where MOTUS randomizes the outcome[28]. In order to know how many seeds are necessary for a statistically relevant outcome, preliminary tests were done. Where the average result of that run would only be 3% or less away from the mean of all runs and this should be within the 95% confidence interval (3% is a chosen acceptance level). This is checked by a student t-distribution, according to Dekking et al. (2005), for the base scenario (with no strategy) with 0% CAVs. This considered outflow, the percentage of deleted vehicles and a total time spent in the system. The student t-distribution value is given by the following equation (D.1):

$$N > t_{\frac{1}{2}a,N-1}(1 + \frac{1}{2}\xi^2)\frac{X_S^2}{X_d^2} \tag{D.1}$$

Where:
N: The sample size varied in the test runs. To determine the minimal amount of seeds to be within the margin of 3% away from the mean.
$t_{\frac{1}{2}a,N-1}$: the value of the student t-distribution (Dekking et al., 2005).
ξ: the normal distribution excess value
a: The desired reliability, the 95% confidence interval
X_d: the accepted deviation of 3%
X_S: the standard deviation of the samples

The first test considered the performance of the model, testing if it works and if there are any anomalies. Once the deleted vehicles (and thus collisions and on-ramp misses, for further explanation see section 4.2) were minimized, a tests on the variation from the mean has been done. With the help of iteration a sample size has been determined. It showed that with 6 seeds, 95% of the data would sit only 3% away from the mean, this is deemed exact

[28] Be aware that this randomness is attached to the seed number, e.g. seed number 3 will give the same result as the previous (or the next) seed number 3 run. Therefore this is seen as a sort of pre-set randomness.

enough. This has been tested for "no"-strategy and 0% CAVs, for the performance indicators of "Outflow", "Deleted vehicles" and "Total time spent in the system (TTSiS)".

D.2. Preliminary tests: The on-ramp demand

1100 veh/hour. Show the contour plots and fundamental diagrams, showing no traffic jams with 900 veh/hour. After the amount of runs per scenario has been determined, the "on-ramp demand" and the "trigger density" [29] are tested, the most suitable single value will be used as a control value in chapter 4. The on-ramp demand was varied between 900 and 1100 vehicles per hour. Since 900 vehicles per hour would sometimes **not** generate a traffic jam, this option was abandoned and 1100 was the variable that was opted.

D.3. Trigger density a.k.a. the density threshold check

The trigger density was initially varied between four variables, starting from the least known density to be a traffic jam (Treiber et al., 2000; Yuan et al., 2015), 35 up to 41 with increments of 2 vehicles per kilometre. The last variable was chosen to be set for two reasons:

1. 35 vehicles/km was found to low at times, causing activation of the strategy when there was no "real" traffic jam yet. This can clearly be seen in figure D.1, where the flow contour plot shows preliminary activation causing a traffic jam downstream of the on-ramp, where it is not wanted. This option was therefore abandoned.

2. 37, 39 and 41 all posed (nearly) the same results with the preliminary tests on two key performance indicators (KPIs): Outflow and an indicator for platoon size. This can be seen in figures D.2 and D.3

When combining these arguments, clarity is the conclusive reason. With 37 one could argue that it is very close to 35, causing accidental activation and 41 [veh/km] performs just as well as 39 [veh/km], where the flow-density contour plots showed the most stability with 41 vehicles per km. All together it presents the final verdict: 41 vehicles per kilometre is to be the trigger density of the strategy.

There is however still an undetermined control variable in the trigger density, namely that of the threshold for the DDLS activation strategy with a permanent density threshold check. The permanent part of this strategy demands that the DDLSs will be deactivated when the density drops below the (or another) threshold. At first the same threshold for the activation process was taken, this caused a lot of sudden lane changes, therefore a hysteresis measure was taken. The deactivation threshold was set at the lowest density threshold, namely 35 [veh/km]. This density worked well ever since.

[29] also known as the density threshold, for the activation of the strategy

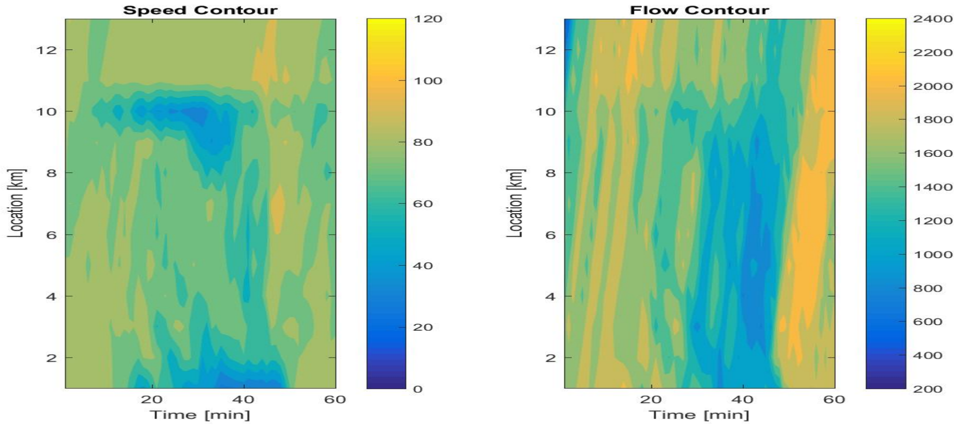


Figure D.1. – Contour plots: With the DDLS activation strategy with a one-time density threshold check, a trigger density of 35, a ramp demand of 1100 and a penetration rate of 2%. A split due to the early activation of the DDLSs is visible.

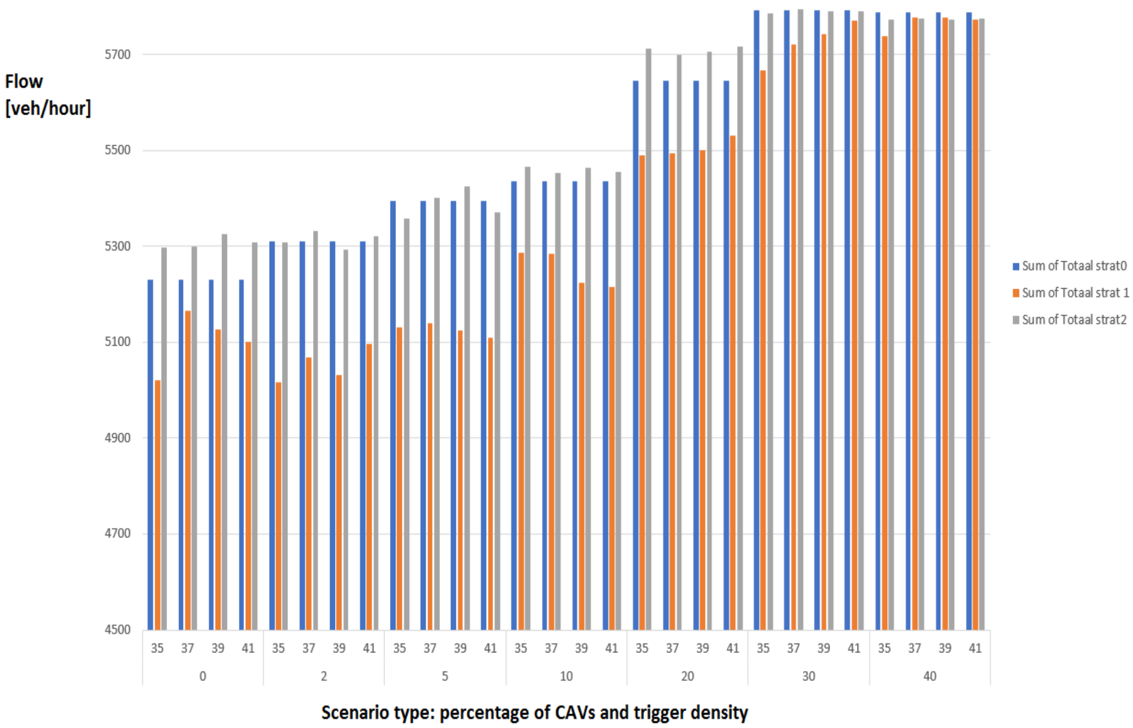


Figure D.2. – Results of all scenarios, considering Outflow

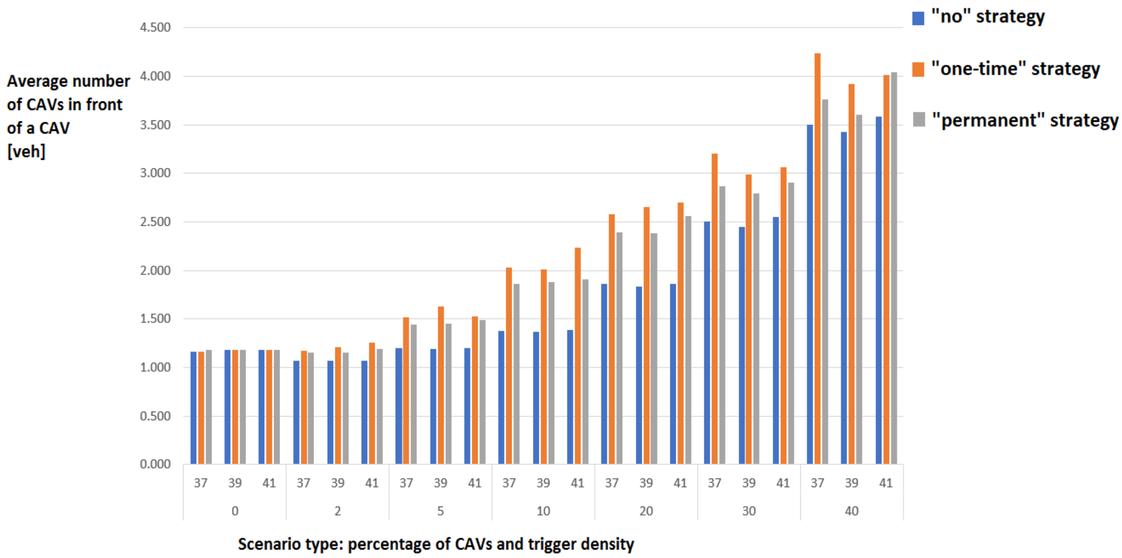


Figure D.3. – Results of all remaining scenarios (37, 39, 41), considering an indication for average platoon formation

Finally, the dimensions of the motorway network are also pre-determined. This was done in the early stages of the set up, but nonetheless important to mention. Appendix D.4 shows the calculations made that determined the maximum length of the dynamic dedicated lane sections.

D.4. The determination of the maximum DDLSs length

Since the upstream on-ramp is the only limitation of the total combined length of the DDLSs, this maximum length has been searched. Another demand for the network design is that it should be in the Netherlands to resemble real world implementation possibilities. Also the road should be congested often, because the designated jam area is the core behind the strategies. Hence the busiest roads were looked at according to the "file top 50" (traffic jam top 50) (VID, 2017). This resulted in the top 2 motorways (A-roads), with the most amount of traffic jam (weighed average). Resulting in a layout of the A27 and the A4. The A4 has the longest stretch of road, without an on- or off-ramp. The 10 kilometres of road were used to build the maximum amount of DDLSs[30], this resulted in the network that is shown below (figure D.4).

[30] 2 km was used for the designated jam area, and 5 could be used for the DDLSs, if 1/3 of the vehicles on the DDLSs had to be added to the back of these 7 km, it would "just" not spill back on the upstream onramp.

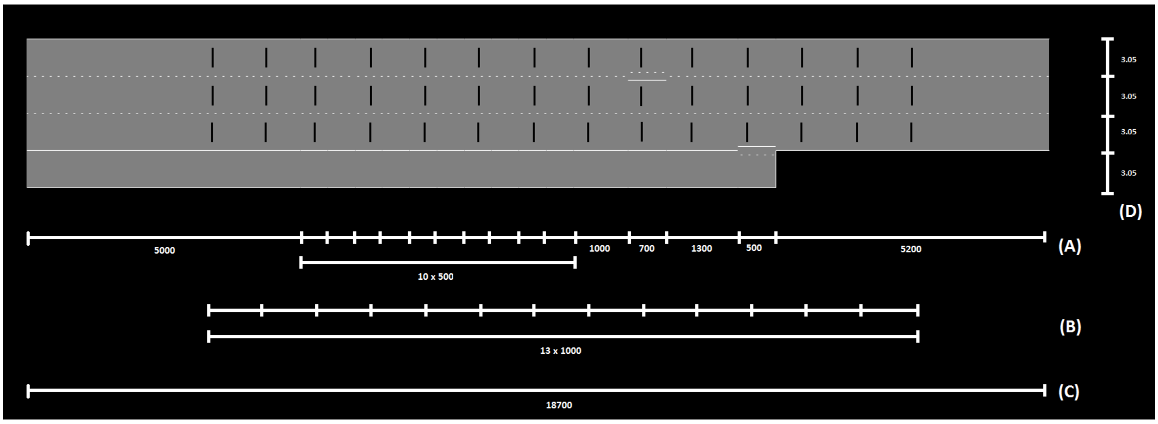


Figure D.4. – Drawing with all the road layout measurements, group (A) divides the road sections, group (B) shows the distance between the detectors, group (C) shows total length and group (D) shows the lateral distance between the lanes.

Appendix E.Validation

In this appendix the data of the simulation of the base scenario is validated by a comparison with empirical evidence of motorway traffic. Since CAVs do not roam the motorway yet, disregarding experiments, the number of observations of the scenarios with CAVs is too small for reliable empirical evidence. The four traffic characteristics used for the validation of the congested control ("no") strategy were: The flow contour plot (and outflow), the fundamental diagram, the capacity drop and the shockwave propagation speed. Also the amount of deleted vehicles are taken into account during this validation.

E.1. Speed contour plots and flow observations

Below in figure E.1 a speed contour plot is shown, these plots explain three traffic characteristics. *1.* It validates the shape and form of a fixed bottleneck due to an on-ramp exceeding the capacity downstream. *2.* The propagation speed of the tail of the bottleneck is validated. *3.* As an extra validation the strategy with an one-time density threshold check is compared to an fundamental diagram of normal traffic with an suddenly closed lane (due to an accident). Furthermore, the increase in throughput due to an increase in CAVs is observed which is also observed by previous research.

The shockwave propagation speed
First of all, according to the literature[31], the shape of the speed contour plot is similar to that of other fixed bottlenecks. The speed of the shockwave propagation upstream can be determined by the slope of the figure, since the axis describe location and time. Figure E.1 shows a shockwave of around 15 kilometres an hour according to equation E.1 and a rough estimation of the values in that equation. Research approximates the shockwave speed at 15-20 km/hour. The rough estimation is right in that window which validates that the model is able to model traffic flow realistically.

$$\omega_{A,B} = \frac{q - A - q_B}{k_A - k_B} \tag{E.1}$$

$\omega_{A,B}$: indicates the propagation speed of the shockwave between state A and B in according to the fundamental diagram.

$q_A - q_B$: indicates the difference of flow in each state of the fundamental diagram.
$k_A - k_B$: indicates the difference of density in each state of the fundamental diagram.

[31] As thought in Traffic flow theory and simulation - CIE4821-09, by V. Knoop

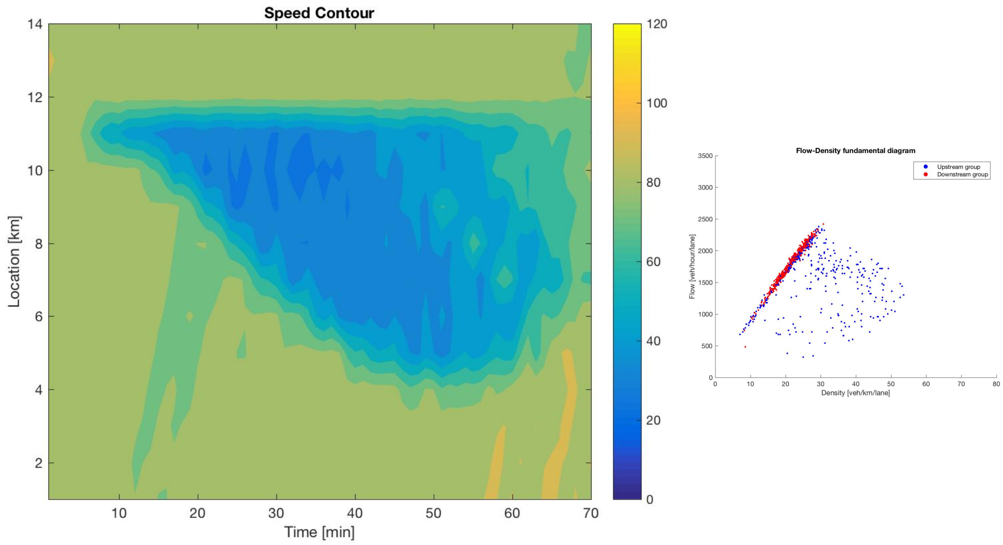


Figure E.1. – Contour plot with no DDLS activation strategy, trigger density 41, ramp demand 1100 and penetration rate 0%, hence the base scenario. A conventional flow contour plot for a traffic jam with a fixed bottleneck (and head of the tail) is visible. To determine the shockwave speed the fundamental diagram of this scenario is added.

Increase in CAVs is increase in throughput

Another observation is that the outflow increases if the CAV penetration rate increases, this is seen in figure E.2. As indicated by van Arem et al. (2006), with 40% CACC equipped vehicles the throughput will benefit. Coincidentally at 40% CAVs there is no longer congestion in this network with the given demand pattern, this is seen in figure E.3. The low switch "on" percentages (right) indicate that the strategy is no longer activated, thus platoon sizes (left)do not longer differ.

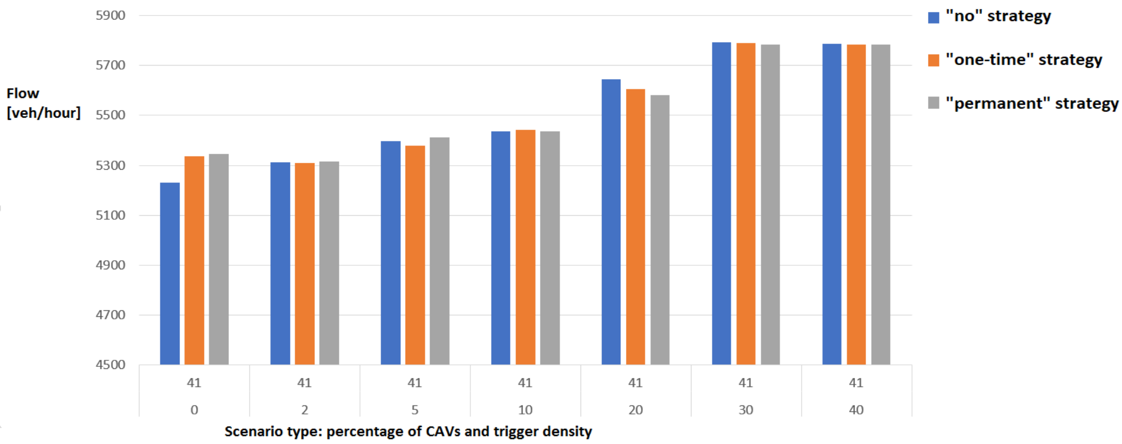


Figure E.2. – Outflow [veh/h] after the bottleneck, for all vehicles.

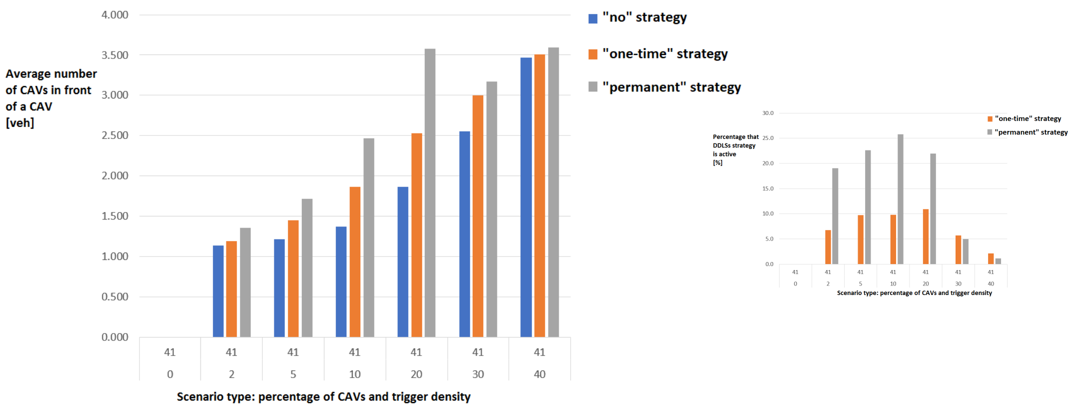


Figure E.3. – An indication of average platoon size, with the weighed average (size of platoon over number of platoons) amount of CAVs directly preceding a particular CAV per penetration level scenario (left), together with the "switch-on" percentages (right).

Accident comparison with the strategies

The strategies are not yet implemented and it appears that no validation could be done on the strategies self. However, it could be argued that the strategy with an one-time density threshold check closes of a lane, as would also occur when an accident happens. This scenario was looked up in literature and a similar speed contour plot is seen (figure E.4) (Kwon and Varaiya, 2005). The bottom left speed contour plot (figure E.4) shows an very similar speed contour plot as seen in figure E.5. The characteristic of the propagation speed of the tail, is very similar also in terms of propagation speed. A rough estimation shows a propagation speed of the strategy of 24 km/hour, the accident has an estimated propagation speed of 18 km/hour. This is not too far off, but in further research it has to be checked if a propagation speed of 24 km/hour is not too dangerous (see section 5.2.3).

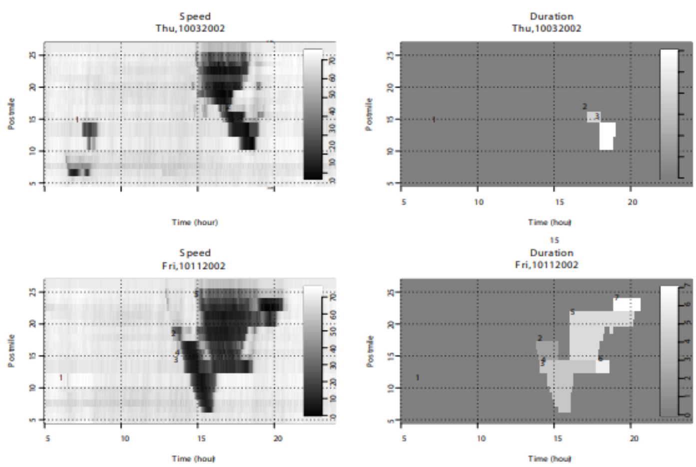


Figure E.4. – Speed contour plots of an accident (Kwon and Varaiya, 2005).

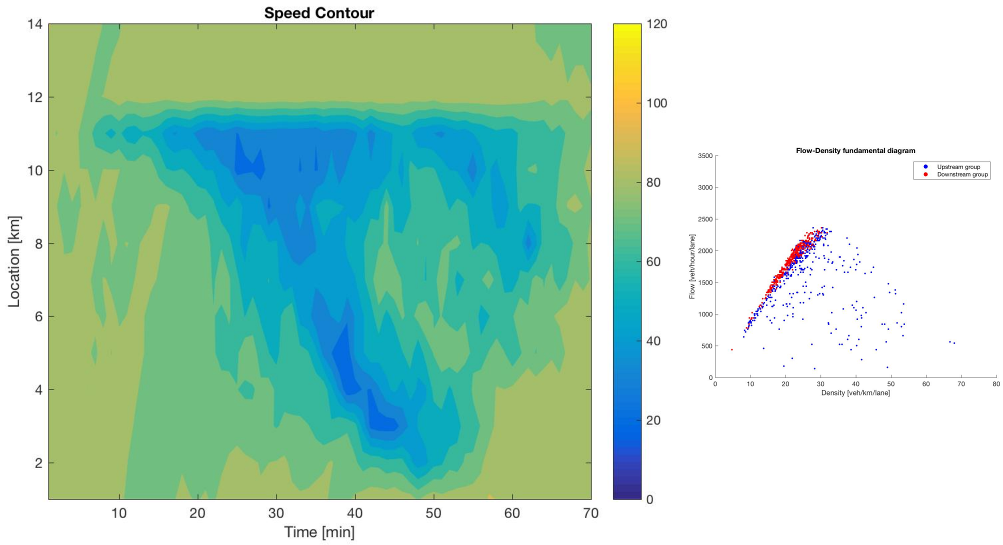


Figure E.5. – Contour plots with a DDLS activation strategy with an one-time density threshold check, trigger density 41, ramp demand 1100 and penetration rate 0%. A speed contour plot for a traffic jam with a fixed bottleneck, with tail and head clearly visible. To determine the shockwave speed the fundamental diagram of this scenario is added.

E.2. Fundamental diagrams and capacity (drop)

Below in in figure E.6 the flow-density fundamental diagram for the control strategy with 0% CAVs is shown. In this figure the maximum flow (in vehicle per hour per lane) for the downstream and upstream cross section is shown. A rough calculation determined that the maximum of the free flow branch of the upstream detector group was 2200 vehicles per hour per lane. The congested branch showed a maximum capacity of 1900 vehicles per hour per lane. This is a capacity drop of 13.6% which is according to standards as shown by Henkens and Tamminga (2015) (between 10% and 15%) and Yuan et al. (2015) (between 3% and 18%). Because the congested branch is widely spread it is hard to distinguish a solid value for the capacity drop, but the line fitted on the capacity drop presented this value.

The maximum free flow capacity lies at (around) 2300 vehicles, this is also determined by Henkens and Tamminga (2015). It has to be said that determining the capacity using the fundamental diagram is very sensitive to fit a line on the plotted data. These two values are enough to validated the simulation model regarding the fundamental diagram.

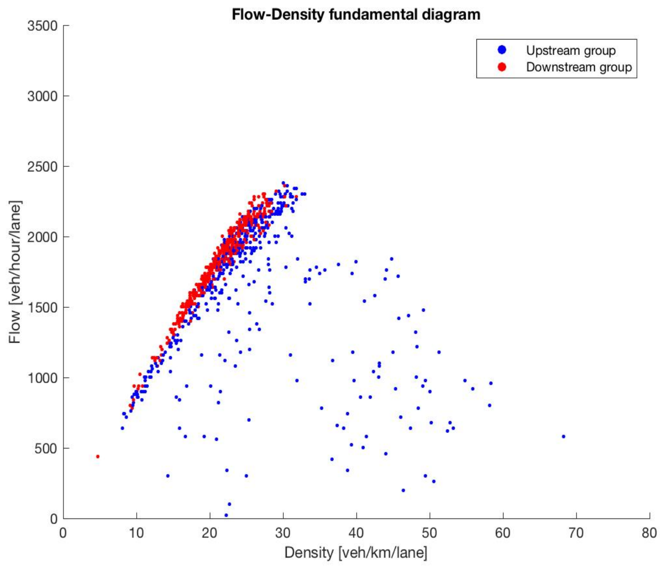


Figure E.6. – fundamental diagram plot, CAV penetration 10%, strategy 2

E.3. Deleted vehicles and merging behaviour

The deleted vehicles as presented in table J.2 and figure5.21. These were less than 1% of the total amount of vehicles. The vehicles that were deleted all took place on the on-ramp, due to difficulties of merging. It is believed that the LMRS model caused the deleted vehicles and therefore the deleted vehicles are accepted. The LMRS gap search function only considers vehicles in its direct surroundings. It does not regard vehicles further down or upstream. A human driver would search for a gap down- or upstream which would give them more possibilities to merge. This caused an over estimation of the amount of vehicles deleted, with a better model, this could be prevented.

Appendix F.

Below there is one example given per strategy, and the difference of both strategies is also explained. For an example with moving images, go to the YouTube pages of: https://youtu.be/UMvCAn4Oxvc and https://youtu.be/i3-B-04_vHg (Hurley et al., 2018). These videos respectively show the strategies with an one-time density threshold check and with a permanent density threshold check.

1. DDLS activation strategy with an one-time density threshold check: This strategy activates a DDLSs section, whenever a traffic jam is detected on the first (most downstream) DDLS, that section then creates a dedicated lane on the left most lane. This proceeds step wise upstream until the last (most upstream) DDLS is reached. If a traffic jam is present on the last DDLS, the left lane no longer becomes dedicated and in stepwise reverse order the DDLSs no longer are dedicated to CAVs. The deactivation is done with the speed of the last CAV, on the last DDLS, in consideration.

The figures below represent the DDLS activation strategy with an one-time density threshold check, the captions below the figure gives the explanation step by step. Predominantly speed is represented, where green is 100 km/h and red is less than 30 km/h.

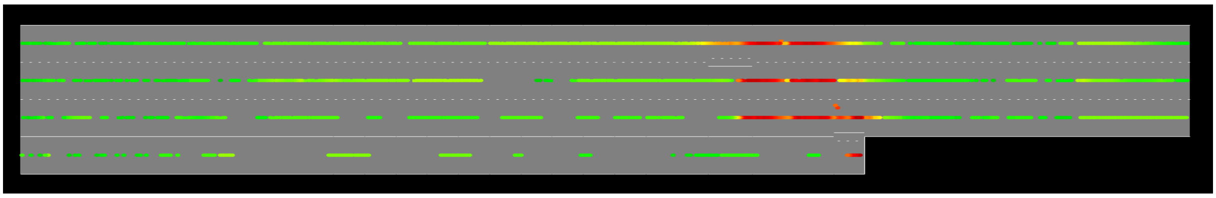


Figure F.1. – Speed representation: The start of the strategy, a standing bottleneck appears in in the designated jam area

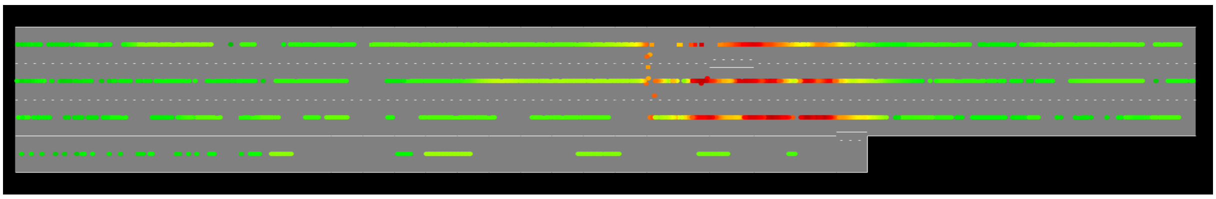


Figure F.2. – Speed representation: As soon as the traffic jam hits the first DDL Section, the first section clears out the for CAVs only. They will be caught by the standing bottleneck in the designated jam area

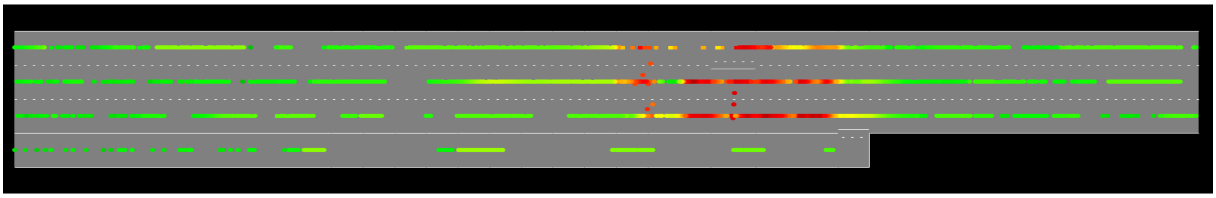


Figure F.3. – Speed representation: This goes stepwise, the next section also becomes dedicated to only CAVs

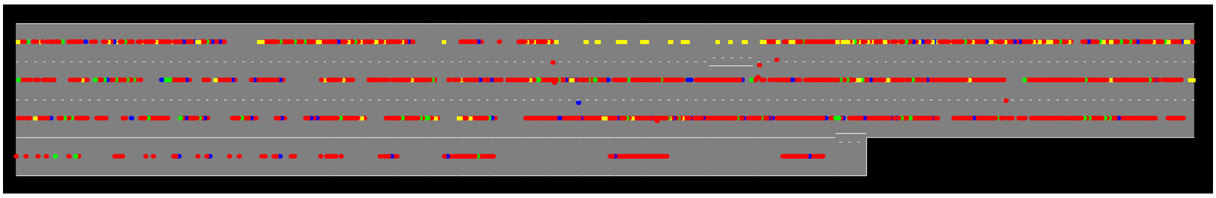


Figure F.4. – Vehicle class representation: The system seems to work (in terms of number of CAV platoons), the yellow vehicles are CAVs.

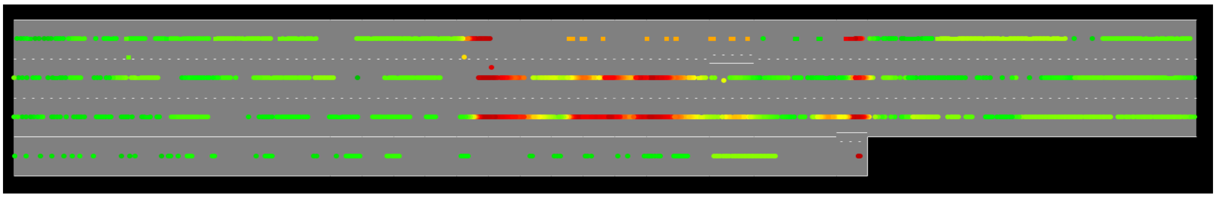


Figure F.5. – Speed representation: It continues to clear the DDLSs for conventional vehicles. As soon as the density threshold is met, the lane stays dedicated. The vehicles still end up in the traffic jam at the bottleneck while the spillback almost reaches the last DDLS. Also the reduced speed of the CAVs is clearly visible (orange colour).

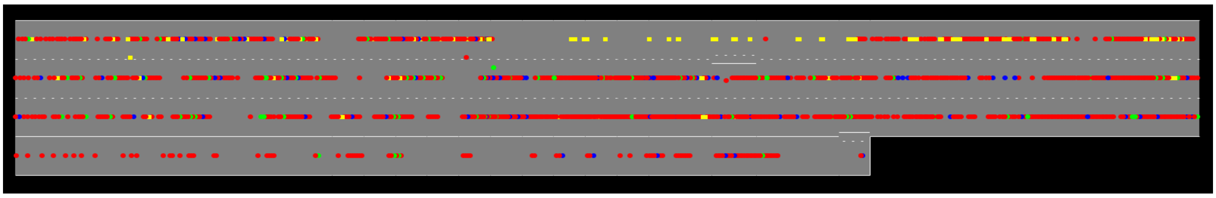


Figure F.6. – Vehicle class representation: The moment in time as figure F.5. By the look of it many platoons have formed!

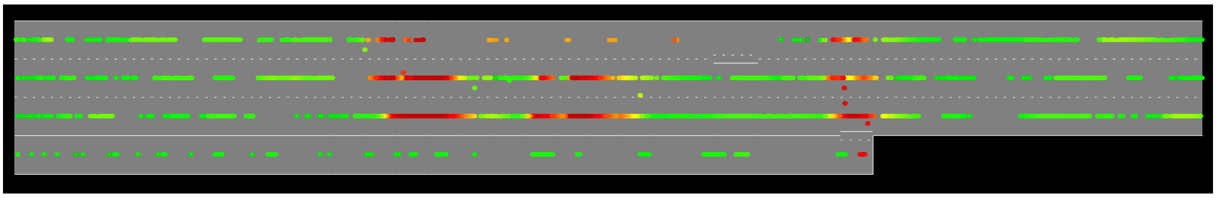


Figure F.7. – Speed representation: The final DDLS is reached, deactivation of the strategy is triggered

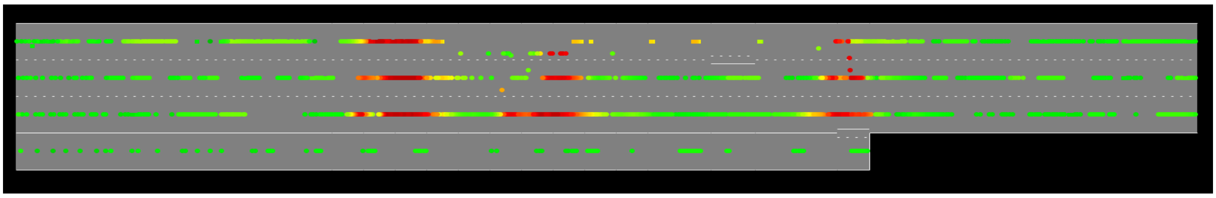


Figure F.8. – Speed representation: The normal vehicles are allowed back again behind the platooning vehicles, in order to close the gap an prevent any (increased) capacity drop

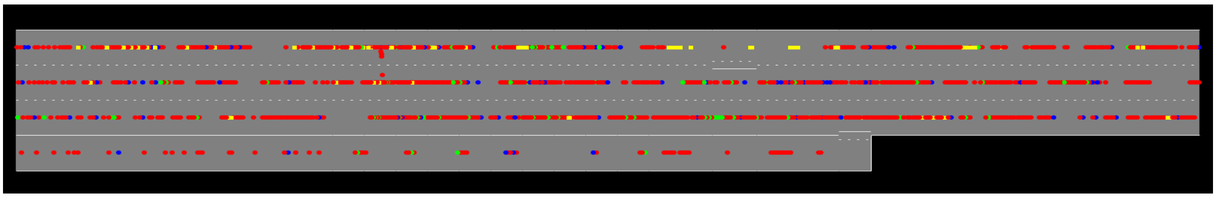


Figure F.9. – Vehicle class representation: The vehicles are (almost) back and divided over all lanes again. Platoons appear to have been formed!

1. DDLS activation strategy with a permanent density threshold check: This strategy works slightly different than the one above. With the DDLS activation strategy with an one-time density threshold check the left lane remained empty, until the deactivation zone was reached (until the last DDLS was congested). This strategy works a bit different, meaning that the left lane will not remain dedicated to CAVs. The left lane only remains dedicated when the threshold is uphold on the current section **and** the section downstream. Meaning the DDLS activation strategy with a permanent density threshold check only turns on when two longitudinal connected sections are congested and only then the section is set to "dedicated".

The figures below represent the DDLS activation strategy with a permanent density threshold check, the captions below the figure give the elaboration.

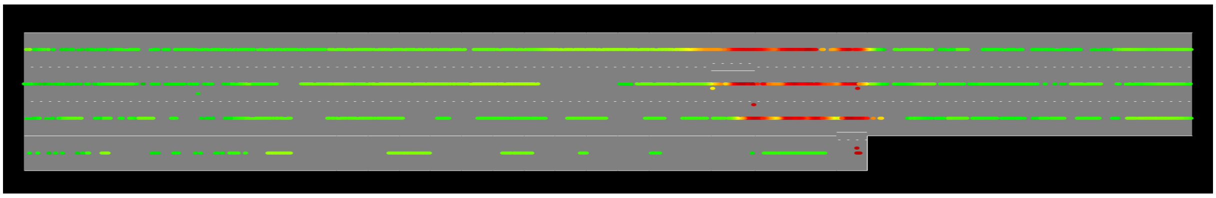


Figure F.10. – Speed representation: The start of the strategy, a standing bottleneck appears in in the designated jam area

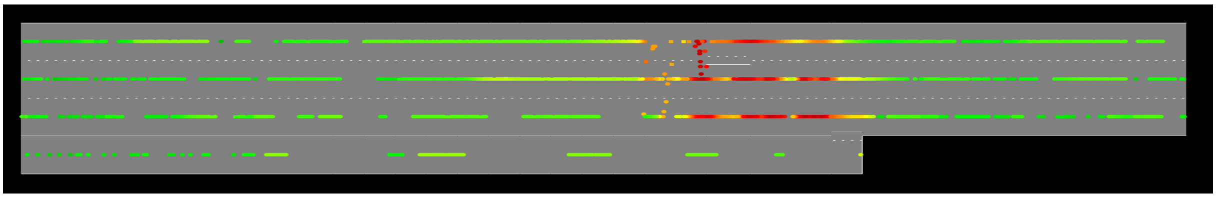


Figure F.11. – Speed representation: As soon as the traffic jam hits the first DDL Section, the first section clears out the for CAVs only, they will be caught by the standing bottleneck

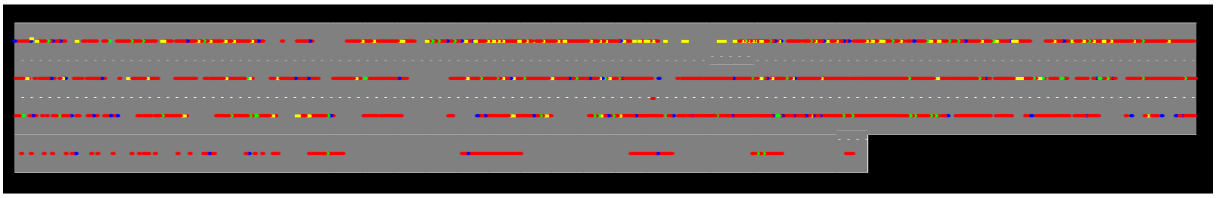


Figure F.12. – Vehicle class representation: As soon as the traffic jam hits the first DDL Section, the first section clears out the for CAVs only, they will be caught by the standing bottleneck

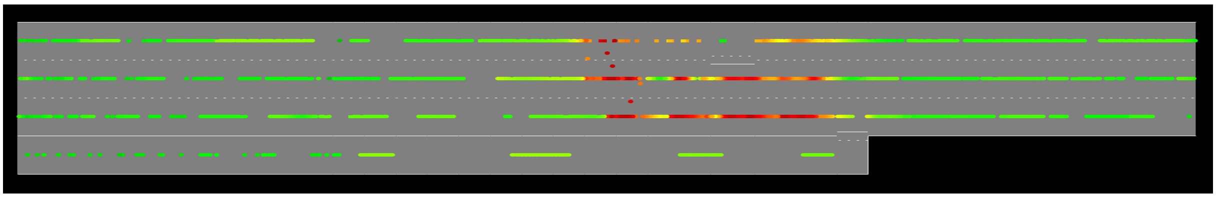


Figure F.13. – Speed representation: The next section also becomes dedicated to only CAVs, just as in the one-time density threshold check activation strategy.

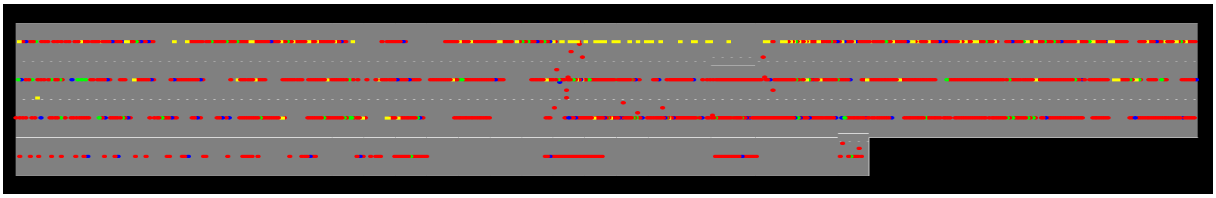


Figure F.14. – Vehicle class representation: The next section also becomes dedicated to only CAVs, just as in the one-time density threshold check activation strategy.

So far the strategy worked exactly the same, but then:

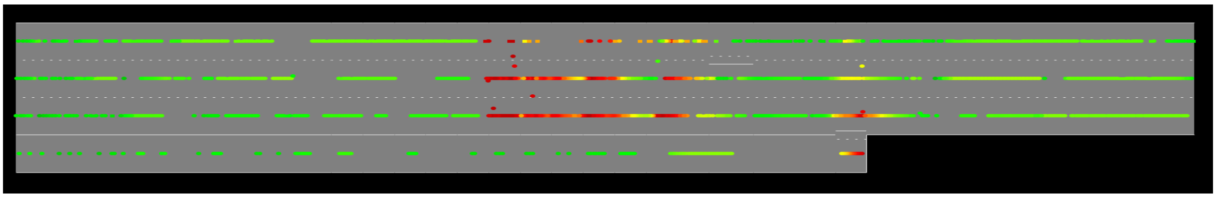


Figure F.15. – Speed representation: The first DDLS (most downstream DDLS) is not congested any more, which means the condition of dedicated for CAVs does not uphold, the conventional vehicles can be seen on the left lane (between the platoons).

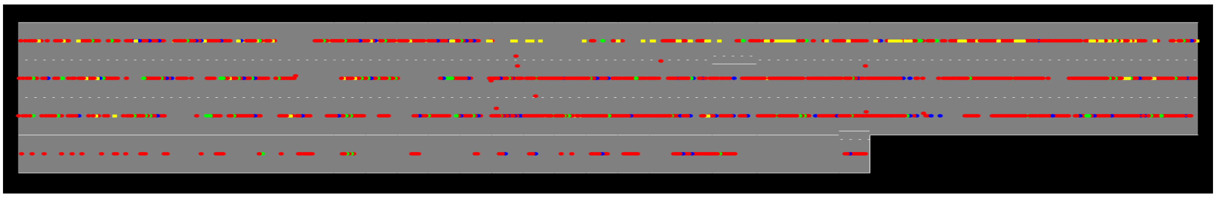


Figure F.16. – Vehicle class representation: The first DDLS (most downstream DDLS) is not congested any more, which means the condition of dedicated for CAVs does not uphold, the conventional vehicles can be seen on the left lane (between the platoons). However, platoons also seemed to have been formed.

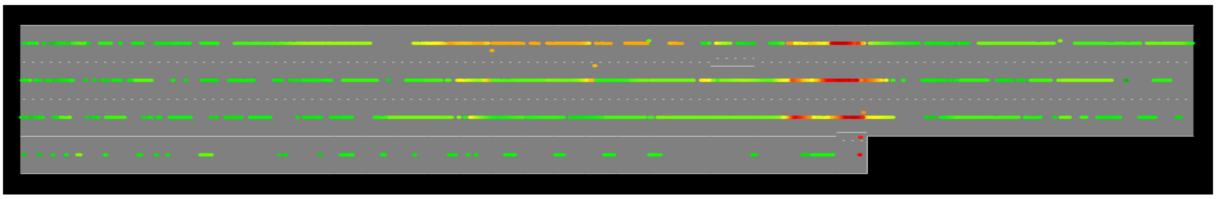


Figure F.17. – Speed representation: quite quick after the the previous step, none of the DDLSs uphold the condition to turn into CAV only lanes.

The two strategies were simulated with a test set up, with: an on-ramp demand of 1000 [veh/h], a CAV penetration rate of 10% and the trigger density set at 36 [veh/km].

Appendix G.

The coding of this lane change process by changing the lane change bias (Xiao et al., 2017) is visible in this section, it shows the conditions as coded in MOTUS (JAVA), presenting in what way the bias is altered (with an **on**-switch). Appendix G.1 shows this for the "DDLS activation strategy with a one-time density threshold check". This is slightly different for the "DDLS activation strategy with a permanent density threshold check", this exemption is explained in subsection 3.4.3. For this strategy there is no switch that holds on to the lane changing bias (one-time threshold check), therefore the vehicle checks the density threshold condition at all times. In order to ensure no flickering of vehicles occurs, the activation density is higher (41) then the deactivation threshold (35). Appendix G.2 shows this strategy as coded in MOTUS.

G.1. Lane changing bias "DDLS activations strategy with a one-time density threshold check"

Below the behaviour of the vehicles as implemented in MOTUS (JAVA) is shown for the strategy with an one-time density threshold check.

```java
/* === LANE CHANGE BIAS === */
double dLeftBias = 0;
double dRightBias = 0;

//for stepwise back set jamTime 3000 or @ 0.
if (jamTime == 5401 &&  (Contains(CAVlaneID_5, vehicle.lane.id()) ||  Contains(CAVlaneID_6, vehicle.lane.id())) && isJammed(JamDensity, vehicle.lane)){

    jamTime = vehicle.model.t();
    //System.out.println(jamTime);
}

/* This is my ON-SWITCH */
if (!SwitchOn)
{
      if ((vehicle.lane.id() == 4 || vehicle.lane.id() == 5 || vehicle.lane.id() == 6) && isNOTJammed(JamDensity, vehicle.lane))
    if (((jPlatoonLane) vehicle.lane).isDynamic() && (vehicle.model.t() <=jamTime || vehicle.model.t() <= strategyStopTime)
            && (isJammed(JamDensity, vehicle.lane.right) || isJammed(JamDensity, vehicle.lane.right.up)) /*&& isJammed(JamDensity,vehicle.lane.down)*/)
    {
        //Keep the bias fixed in the bias below.
        SwitchOn = true;
          if (vehicle.classID == 4)
          {
              vehicle.vMax = 130;
          }
    }
}
/* This is my OFF-SWITCH*/
if (SwitchOn && (vehicle.model.t()>= jamTime || vehicle.model.t()>= strategyStopTime))
{
    SwitchOn = false;
}
/* ------------------------------------------------------------------
   Change of speed limit
--------------------------------------------------------------------*/
/* This is my FAKE TRAFFIC LIGHT*/
if(SwitchOn && vehicle.classID == 4 && (vehicle.lane.id() == 37 || Contains(CAVlanes,vehicle.lane.id())))
{
    vehicle.vMax = 50;
    //System.out.println(vehicle.model.t());
}
else
{
```

Figure G.1. – Java Code, DDLS activation strategy with an one-time density threshold check, part I

```java
{
    vehicle.vMax = 50;
    //System.out.println(vehicle.model.t());
}
else
{
    vehicle.vMax =130;
}

/* ---------------------------------------------------------------------
   The strategy
-----------------------------------------------------------------------*/

/* Lanechanging behaviour*/
if (SwitchOn){
    if (isEquipped)
    {
        dRightBias = Double.NEGATIVE_INFINITY;
        dLeftBias = 0.9;
    }
    //if on left lane
    else if (!isEquipped && vehicle.lane.left == null)
    {
        dRightBias = 0.9;
        dLeftBias = -1;
    }
    //if in middle lane
    else if(!isEquipped && vehicle.lane.left != null && vehicle.lane.right != null)
    {
        dRightBias = dFree;
        dLeftBias = Double.NEGATIVE_INFINITY;
    }
    //if in right lane
    else
    {
        dRightBias = 0;
        dLeftBias = 0;
    }
}


/* === TOTAL DESIRE
```

Figure G.2. – Java Code, DDLS activation strategy with an one-time density threshold check, part II

```java
/* === TOTAL DESIRE ===
 * Depending on the level of desire from the route (mandatory),
 * the speed and keep right (voluntary) incentives may be
 * included partially or not at all. If the incentives are in
 * the same direction, voluntary incentives are fully included.
 * Otherwise, the voluntary incentives are less and less
 * considered within the range dSync < |dRoute| < dCoop. The
 * absolute value of dRoute is used as negative values may also
 * dominate voluntary incentives.
 */
double thetaLeft = 0; // Assume not included
double dVoluntary = dLeftSpeed+dLeftBias+dLeftIntersection;
if (dLeftRoute*dVoluntary>=0 || Math.abs(dLeftRoute)<=dSync) {
    // Same direction or low mandatory desire
    thetaLeft = 1;
} else if (dLeftRoute*dVoluntary<0 &&
        dSync<Math.abs(dLeftRoute) && Math.abs(dLeftRoute)<dCoop) {
    // Voluntary incentives paritally included
    thetaLeft = (dCoop-Math.abs(dLeftRoute)) / (dCoop-dSync);
}
dLeft = dLeftRoute + thetaLeft*dVoluntary;
// Idem. for right
double thetaRight = 0;
dVoluntary = dRightSpeed+dRightBias+dRightIntersection;
if (dRightRoute*dVoluntary>=0 || Math.abs(dRightRoute)<=dSync) {
    thetaRight = 1;
} else if (dRightRoute*dVoluntary<0 &&
        dSync<Math.abs(dRightRoute) && Math.abs(dRightRoute)<dCoop) {
    thetaRight = (dCoop-Math.abs(dRightRoute)) / (dCoop-dSync);
}
dRight = dRightRoute + thetaRight*dVoluntary;

/* === GAP ACCEPTANCE ===
```

Figure G.3. – Java Code, DDLS activation strategy with an one-time density threshold check, part III

G.2. Lane changing bias "DDLS activations strategy with a permanent density threshold check"

Below the behaviour of the vehicles as implemented in MOTUS (JAVA) is shown for the strategy with a permanent density threshold check.

```java
/* === LANE CHANGE BIAS ===
 * Drivers have to keep right. It is assumed that this is only
 * obeyed in free flow and when the anticipated speed on the
 * right lane is equal to the desired speed. Or in other words,
 * when there is no slower vehicle nearby in the right lane.
 * The bias is equal to the free threshold, just triggering
 * drivers to change in free conditions. Another condition is
 * that there should be no route undesire towards the right
 * whatsoever.*/
double dLeftBias = 0;
double dRightBias = 0;

/* ---------------------------------------------------------------------
   This is the switch section
---------------------------------------------------------------------*/
/* This is my ON-SWITCH*/
if (!SwitchOn)
{
    if (((jPlatoonLane) vehicle.lane).isDynamic() && isJammed(JamDensity,vehicle.lane.right)
        && isJammed(JamDensity,getRightLane(vehicle.lane.down)) && vehicle.model.t()<=strategyStopTime /*&& isJammed(JamDensity,vehicle.lane.down)*/)
    {
        SwitchOn = true;
    }
}
/* This is my OFF-SWITCH*/
if (SwitchOn && !((jPlatoonLane) vehicle.lane).isDynamic())
{
    SwitchOn = false;
}
/* This is my Speed limitation during the ON period*/
if (SwitchOn && vehicle.classID == 4 && Contains(CAVlanes, vehicle.lane.id()))
{
    vehicle.vMax=50;
}
else if (!SwitchOn)
{
    vehicle.vMax = 130;
}
/* ---------------------------------------------------------------------
   This is the Dynamic strategy part.
---------------------------------------------------------------------*/
```

Figure G.4. – Java Code, DDLS activation strategy with a permanent density threshold check, part I

```java
    vehicle.vMax=50;
}
else if (!SwitchOn)
{
    vehicle.vMax = 130;
}
/* ---------------------------------------------------------------------
   This is the Dynamic strategy part.
---------------------------------------------------------------------*/
if (((jPlatoonLane) vehicle.lane).isDynamic() && isJammed(JamDensity,vehicle.lane.right)
        && isJammed(JamDensity,getRightLane(vehicle.lane.down)) && vehicle.model.t()<=strategyStopTime)
{
    if (isEquipped)
    {
        dRightBias = Double.NEGATIVE_INFINITY;
        dLeftBias = 0.9;

    }
    //left lane
    else if (!isEquipped && vehicle.lane.left == null)
    {
        dRightBias = 0.9;
        dLeftBias = -1;
    }
    //Middlelane
    else if(!isEquipped && vehicle.lane.left != null && vehicle.lane.right != null)
    {
        dRightBias = dFree;
        dLeftBias = Double.NEGATIVE_INFINITY;
    }
    //right lane
    else
    {
        dRightBias = 0;
        dLeftBias = 0;
    }
}
/* === TOTAL DESIRE ===
 * Depending on the level of desire from the route (mandatory),
```

Figure G.5. – Java Code, DDLS activation strategy with a permanent density threshold check, part II

```java
            dRightBias = dFree;
            dLeftBias = Double.NEGATIVE_INFINITY;
        }
        //right lane
        else
        {
            dRightBias = 0;
            dLeftBias = 0;
        }
    }
    /* === TOTAL DESIRE ===
     * Depending on the level of desire from the route (mandatory),
     * the speed and keep right (voluntary) incentives may be
     * included partially or not at all. If the incentives are in
     * the same direction, voluntary incentives are fully included.
     * Otherwise, the voluntary incentives are less and less
     * considered within the range dSync < |dRoute| < dCoop. The
     * absolute value of dRouite is used as negative values may also
     * dominate voluntary incentives.
     */
    double thetaLeft = 0; // Assume not included
    double dVoluntary = dLeftSpeed+dLeftBias+dLeftIntersection;
    if (dLeftRoute*dVoluntary>=0 || Math.abs(dLeftRoute)<=dSync) {
        // Same direction or low mandatory desire
        thetaLeft = 1;
    } else if (dLeftRoute*dVoluntary<0 &&
            dSync<Math.abs(dLeftRoute) && Math.abs(dLeftRoute)<dCoop) {
        // Voluntary incentives paritally included
        thetaLeft = (dCoop-Math.abs(dLeftRoute)) / (dCoop-dSync);
    }
    dLeft = dLeftRoute + thetaLeft*dVoluntary;
    // Idem. for right
    double thetaRight = 0;
    dVoluntary = dRightSpeed+dRightBias+dRightIntersection;
    if (dRightRoute*dVoluntary>=0 || Math.abs(dRightRoute)<=dSync) {
        thetaRight = 1;
    } else if (dRightRoute*dVoluntary<0 &&
            dSync<Math.abs(dRightRoute) && Math.abs(dRightRoute)<dCoop) {
        thetaRight = (dCoop-Math.abs(dRightRoute)) / (dCoop-dSync);
    }
    dRight = dRightRoute + thetaRight*dVoluntary;

    /* === GAP ACCEPTANCE ===
```

Figure G.6. – Java Code, DDLS activation strategy with a permanent density threshold check, part III

Appendix H.

Table H.1. – Total outflow in vehicles per hour, out of the traffic jam (after the bottleneck)

Total outflow [veh/h] Activation strategy vs. Penetration level	"No" Strategy.	One-time Strategy	Δ	Permanent Strategy	Δ
pCAV0%TrigDens41	5231	5338	106	5346	115
pCAV2%TrigDens41	5311	5310	-1	5316	5
pCAV5%TrigDens41	5396	5379	-17	5411	16
pCAV10%TrigDens41	5436	5441	6	5436	0
pCAV20%TrigDens41	5645	5605	-40	5582	-63
pCAV30%TrigDens41	5793	5789	-4	5783	-10
pCAV40%TrigDens41	5788	5785	-3	5785	-3

Table H.2. – CAV-only Outflow in vehicles per hour, out of the traffic jam (after the bottleneck).

Outflow CAVs only [veh/h] Activation strategy vs. Penetration level	"No" Strategy.	One-time Strategy	Δ	Permanent Strategy	Δ
pCAV0%TrigDens41	0	0	0	0	0
pCAV2%TrigDens41	93	92	-1	93	0
pCAV5%TrigDens41	231	231	0	236	5
pCAV10%TrigDens41	444	449	4	455	10
pCAV20%TrigDens41	977	967	-10	974	-3
pCAV30%TrigDens41	1516	1518	3	1517	1
pCAV40%TrigDens41	2023	2028	5	2026	4

Table H.3. – non-CAV Outflow in vehicles per hour, out of the traffic jam (after the bottleneck).

Outflow non-CAVs [veh/h]					
Activation strategy vs. Penetration level	**"No" Strategy.**	**One-time Strategy**	**Δ**	**Permanent Strategy**	**Δ**
pCAV0%TrigDens41	5231	5338	106	5346	115
pCAV2%TrigDens41	5218	5218	0	5223	5
pCAV5%TrigDens41	5164	5148	-17	5175	11
pCAV10%TrigDens41	4991	4993	1	4981	-10
pCAV20%TrigDens41	4669	4638	-30	4608	-61
pCAV30%TrigDens41	4277	4271	-7	4266	-11
pCAV40%TrigDens41	3766	3757	-9	3759	-7

Appendix I.

I.1. TTSiS for all vehicles

The total time spent in the system for all vehicles on the main motorway, excluding the vehicles that drive on the on-ramp. The vehicles driving on the on-ramp are merely present to ensure a traffic jam.

Table I.1. – All vehicles total time spent in the system in seconds

Total TSiS [s] **Activation strategy vs. Penetration level**	**No Strategy.**	**One-time Strategy**	**Δ**	**Permanent Strategy**	**Δ**
pCAV0%TrigDens41	6598614	6629800	31186	6640841	42227
pCAV2%TrigDens41	6649601	6657119	7518	6636448	-13153
pCAV5%TrigDens41	6603830	6611719	7889	6615592	11762
pCAV10%TrigDens41	6585333	6592444	7111	6593773	8440
pCAV20%TrigDens41	6487670	6538819	51149	6551832	64162
pCAV30%TrigDens41	6427892	6458896	31004	6472124	44233
pCAV40%TrigDens41	6367581	6412894	45313	6419967	52387

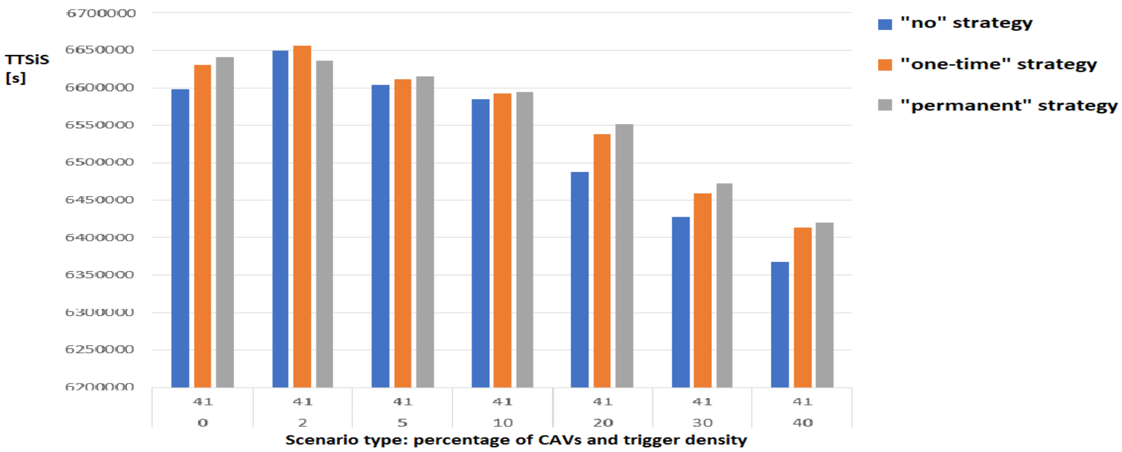


Figure I.1. – TTSiS of all vehicles

I.2. TTSiS of CAVs only

The total time spent in the system for the CAVs only on the main motorway.

Table I.2. – CAVs only total time spent in the system in seconds

Only-CAVs, TTSiS [s] **Activation strategy vs. Penetration level**	**"No" Strategy.**	**One-time Strategy**	**Δ**	**Permanent Strategy**	**Δ**
pCAV0%TrigDens41	0	0	0	0	0
pCAV2%TrigDens41	133919	129281	-4638	128596	-5322
pCAV5%TrigDens41	330060	321331	-8729	315623	-14436
pCAV10%TrigDens41	631139	616988	-14151	608136	-23003
pCAV20%TrigDens41	1293011	1274710	-18301	1271281	-21730
pCAV30%TrigDens41	1922684	1917028	-5657	1917000	-5684
pCAV40%TrigDens41	2536775	2557247	20472	2557194	20418

The results in the table are plotted in figure I.2.

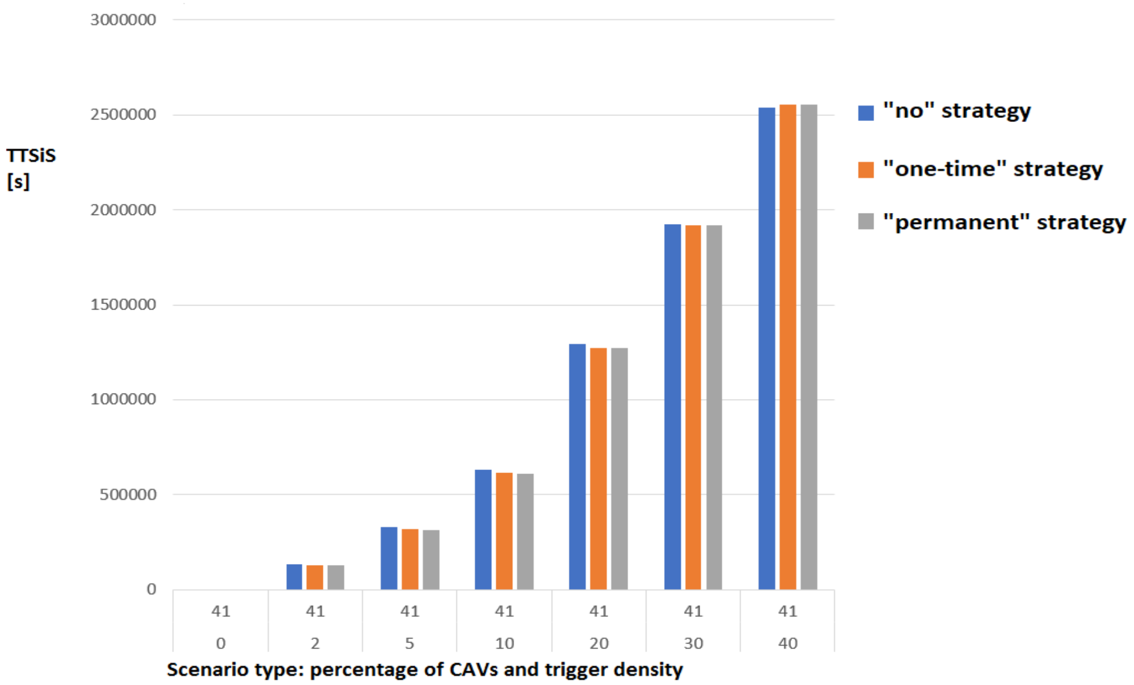


Figure I.2. – TTSiS of CAVs only.

I.3. TTSiS of non-CAVs only

The total time spent in the system for the conventional vehicles (non-CAVs) only on the main motorway.

Table I.3. – Non-CAVs total time spent in the system in seconds

Non-CAVs, TTSiS [s] Activation strategy vs. Penetration level	**"No" Strategy.**	**One-time Strategy**	**Δ**	**Permanent Strategy**	**Δ**
pCAV0%TrigDens41	6598614	6629800	31186	6640841	42227
pCAV2%TrigDens41	6515683	6527839	12156	6507852	-7831
pCAV5%TrigDens41	6273770	6290388	16618	6299968	26198
pCAV10%TrigDens41	5954194	5975456	21261	5985637	31443
pCAV20%TrigDens41	5194659	5264109	69450	5280550	85891
pCAV30%TrigDens41	4505207	4541868	36661	4555124	49917
pCAV40%TrigDens41	3830806	3855646	24841	3862774	31968

The results in the table are plotted in figure I.3.

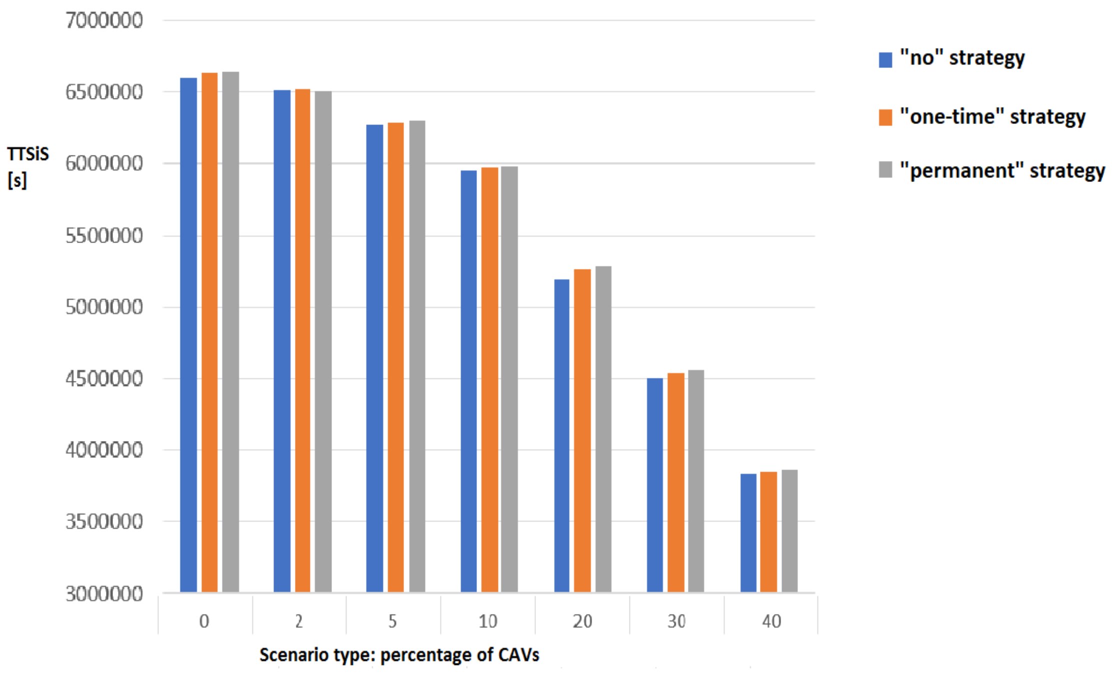


Figure I.3. – TTSiS of non-CAVs only.

The TTSiS in combination with the total number of vehicles counted can determine the average time the vehicles spent in the network. Because the demand was set (section 4.4) the average time the vehicles spent will vary linearly according to the TTSiS. According to the demand pattern 7000 vehicles entered the network. When the simulation was stopped, around 1000 vehicles remained in the network in free flow conditions (for all scenarios). Because the number of vehicles remaining in the network is similar for each scenario (due to the fixed demand pattern) and this is in similar conditions (free flow) and because the data gathering had some double counting issues, the amount of vehicles that were taken into account was 6700. 300 vehicles in similar free flow conditions were cut from the simulation time, because of the similar conditions with the same demand pattern this should not influence the outcome of the strategy comparison.

The average time the vehicles spend in the network was 975 second, or 16.3 minutes.

Appendix J.

J.1. Average platoon size indication

In order to quantify the purpose of this research, namely (active) platoon formation, an indication of the size of the platoons formed and an indication of the number of platoons is presented. This table below (table J.1) presents the weighed average of the platoon size per per scenario (per CAV penetration rate). The average between the size of the platoons is weighed over the number of platoons formed (including the CAVs that drive alone, in a platoon of 1).

Table J.1. – Average platoon size indication, by the average number of preceding CAVs directly in front of another CAV. It is important to know that this number is averaged out over the entire time the simulation ran, also when the dedication was not active.

Average platoon size indication					
Activation strategy vs. Penetration level	**No Strategy.**	**One-time Strategy**	Δ	**Permanent Strategy**	Δ
pCAV0%TrigDens41	0.000	0.000	0.0	0.000	0.000
pCAV2%TrigDens41	1.14	1.19	0.1	1.36	0.221
pCAV5%TrigDens41	1.22	1.45	0.2	1.72	0.500
pCAV10%TrigDens41	1.37	1.86	0.5	2.47	1.097
pCAV20%TrigDens41	1.87	2.53	0.7	3.58	1.710
pCAV30%TrigDens41	2.55	3.00	0.5	3.17	0.619
pCAV40%TrigDens41	3.47	3.51	0.0	3.59	0.121

J.2. Number of deleted vehicles

The table below presents the amount of deleted vehicles per scenario per strategy. The percentage of deleted vehicles is 1% or less of the total amount of vehicles (7000, according to the demand pattern)

Table J.2. – Number of deleted vehicles (over 6 seeds, so fractions can occur).

No. of deleted vehicles **Activation strategy vs. Penetration level**	**No Strategy.**	**One-time Strategy**	Δ	**Permanent Strategy**	Δ
pCAV0%TrigDens41	5.0	5.00	0.000	5.00	0.000
pCAV2%TrigDens41	5.0	5.00	0.000	5.00	0.000
pCAV5%TrigDens41	5.0	5.00	0.000	5.00	0.000
pCAV10%TrigDens41	5.0	5.00	0.000	5.00	0.000
pCAV20%TrigDens41	21.0	21.00	0.000	21.00	0.000
pCAV30%TrigDens41	32.2	44.83	12.667	46.00	13.833
pCAV40%TrigDens41	62.3	67.67	5.333	65.67	3.333

J.3. Percentage of time the strategy was active [%]

Table J.3. – Percentage of time the strategy was active [%].

Percentage of time the strategy was active. **Activation strategy vs. Penetration level**	**One-time Strategy**	**Permanent Strategy**
pCAV0%TrigDens41	0.000	0.000
pCAV2%TrigDens41	6.73	19.07
pCAV5%TrigDens41	9.72	22.63
pCAV10%TrigDens41	9.76	25.81
pCAV20%TrigDens41	10.94	21.97
pCAV30%TrigDens41	5.67	4.95
pCAV40%TrigDens41	2.16	1.13

Appendix K.

K.1. Speed contour plots of all 21 scenarios

Below in figure K.1 the speed contour plot of the base scenario ("no" strategy) with 0% CAVs is given as an example of the orientation of the speed contour plots in figure K.2.

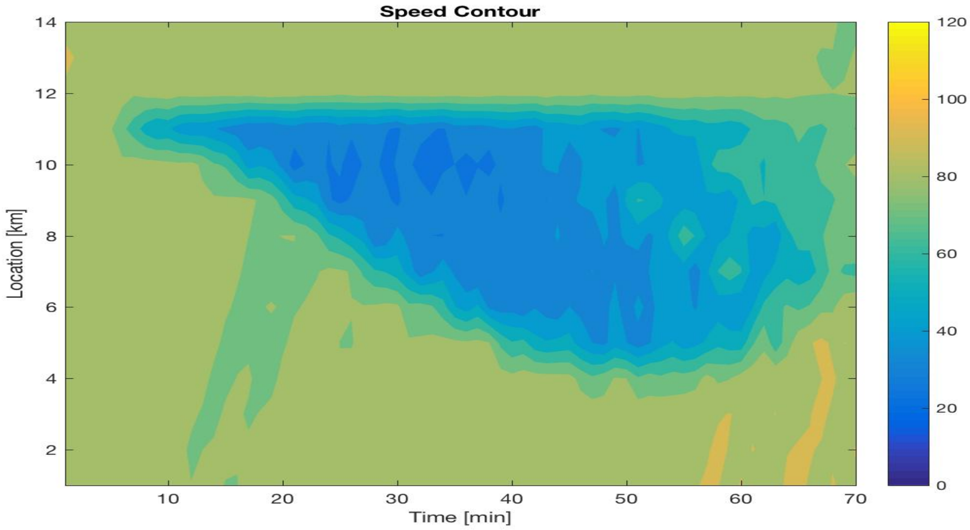
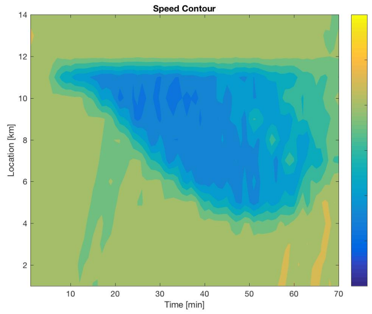
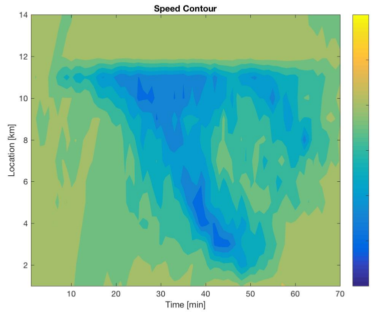
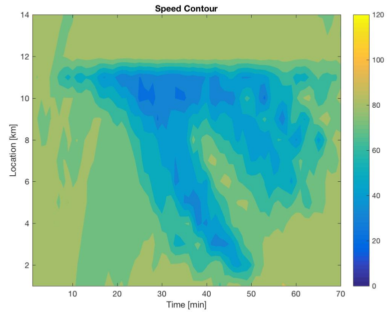


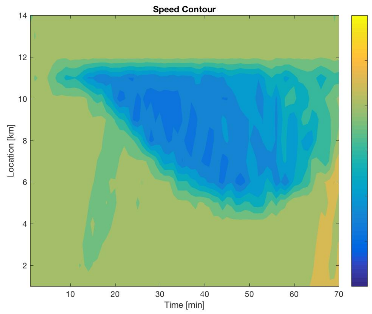
Figure K.1. – Speed contour plot. On the y-axis the location [km] is given, starting at the first detector. The x-axis describes the time. Speed is given indicated by the colour bar on the right-hand side of the figure

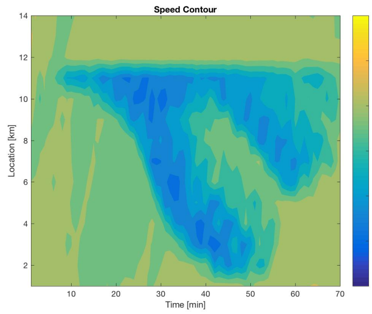
Below in figure K.2 speed contour plots of both strategies show a similar volume and shape although more shockwaves can be seen in the DDLSs activation strategy with a permanent density threshold check (the left column). The shape of the speed contour plots of the strategies differ from the speed contour plots having "no" strategy; there are no shockwaves and the form indicates one dense traffic jam with no stop-and-go waves (Treiber et al., 2000). The overall volume of the shape is similar which would indicate the lost time would be similar (see appendix I. It can be seen that the one-time strategy keeps the lane dedicated during the time the strategy is active, there is a larger gap after the first shockwave, indicating less dense traffic. This is due to a temporary fixed dedicated lane. This causes less stop-and go behaviour, but the capacity is not fully used (a longer time with an empty lane).

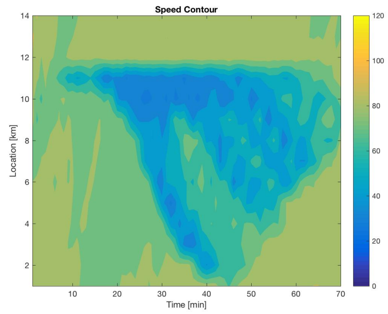

Speed Contour
Location [km]
Time [min]

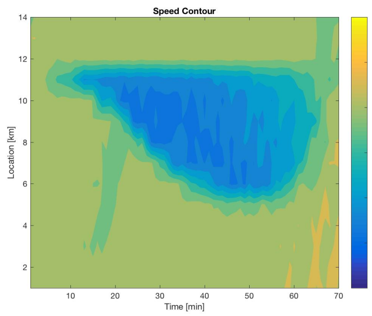

Speed Contour
Location [km]
Time [min]

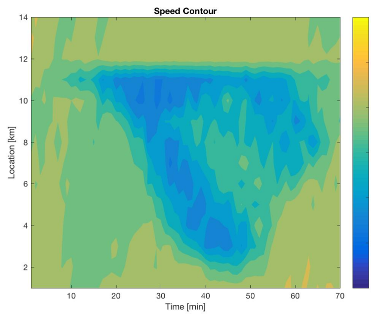

Speed Contour
Location [km]
Time [min]

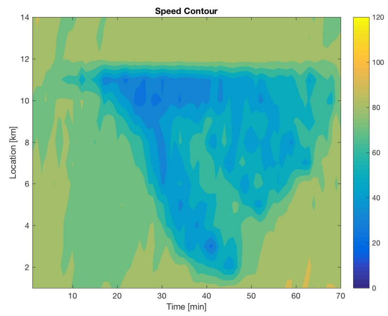

Speed Contour
Location [km]
Time [min]

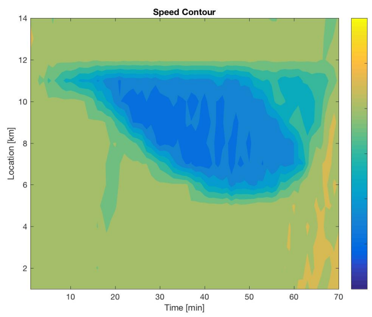

Speed Contour
Location [km]
Time [min]

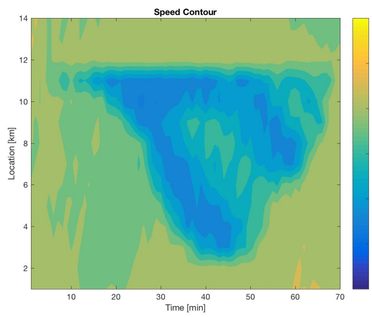

Speed Contour
Location [km]
Time [min]

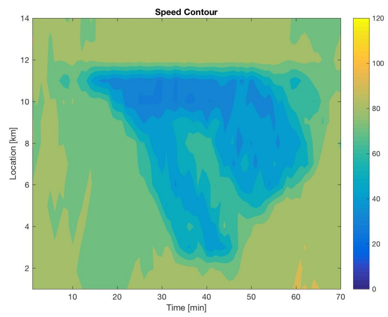

Speed Contour
Location [km]
Time [min]


Speed Contour
Location [km]
Time [min]


Speed Contour
Location [km]
Time [min]


Speed Contour
Location [km]
Time [min]


Speed Contour
Location [km]
Time [min]


Speed Contour
Location [km]
Time [min]

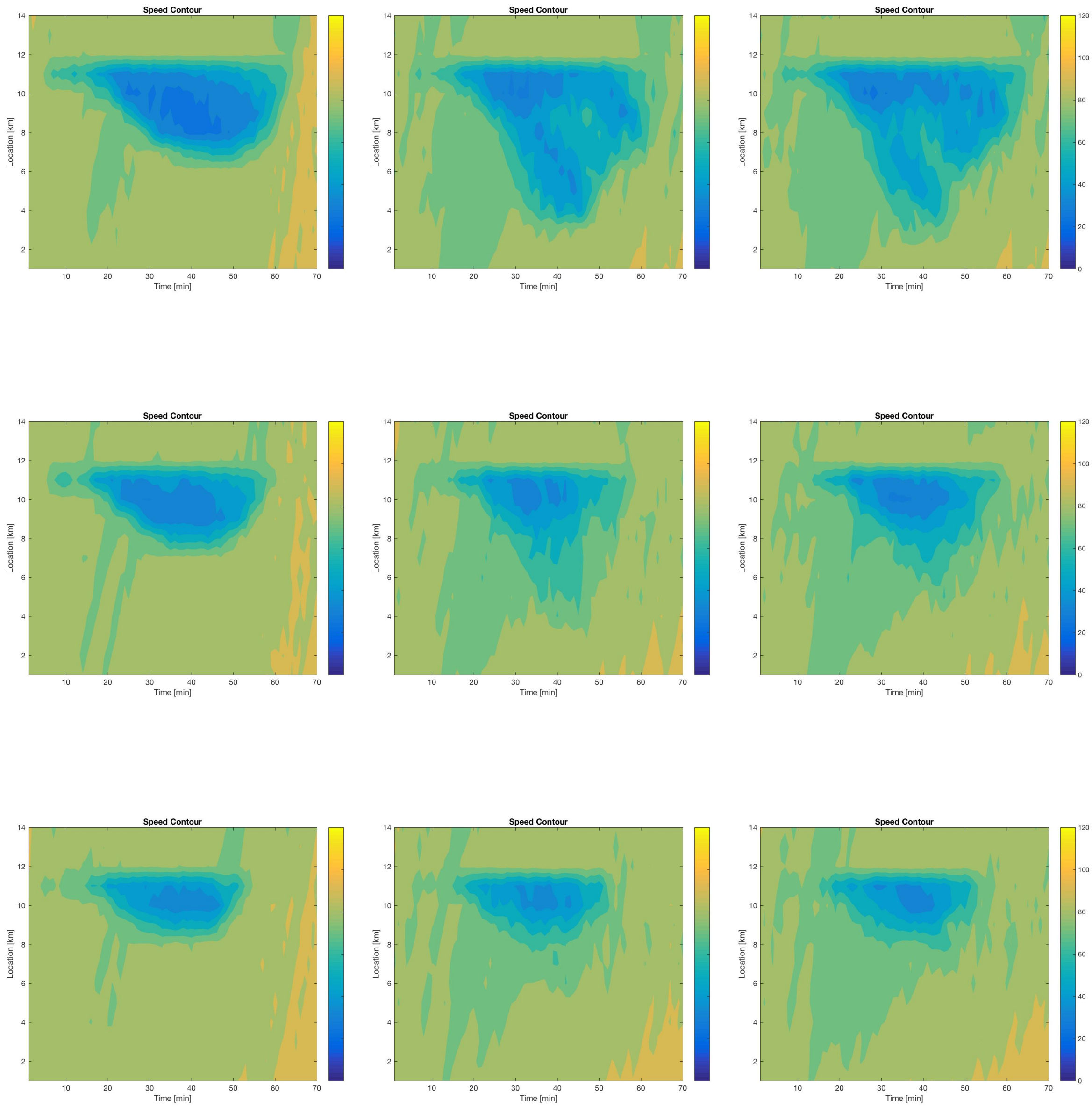


Figure K.2. – All speed contour plots of all 21 scenarios, the left column shows the base scenario ("no"strategy), the middle column shows the strategy with an one-time density threshold check and the right column shows the strategy with a permanent density threshold check. The seven scenarios (the rows) show the penetration rate of the CAVs in a ascending order (from top to bottom: 0%, 2%, 5%, 10%, 20%, 30% and 40%).

K.2. On-Switch detection per CAV

Below in figure K.3 the on-switch detection per CAV of a random scenario is given as an example of the orientation of the on-switch detection per CAV figures presented in figure K.4.

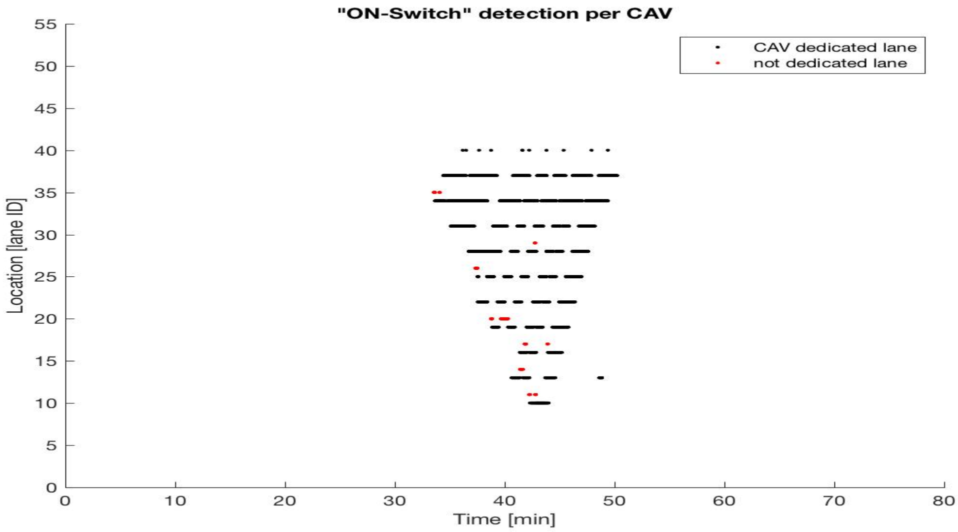
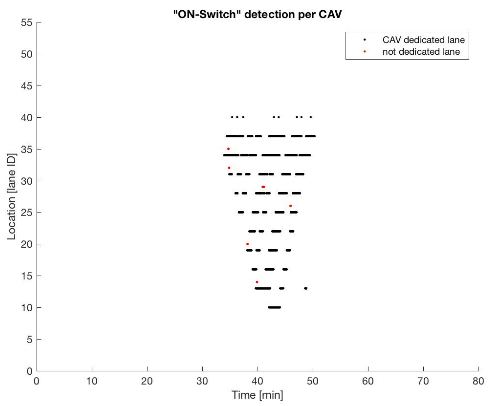
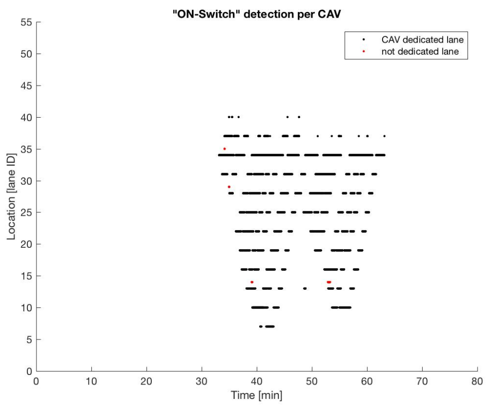


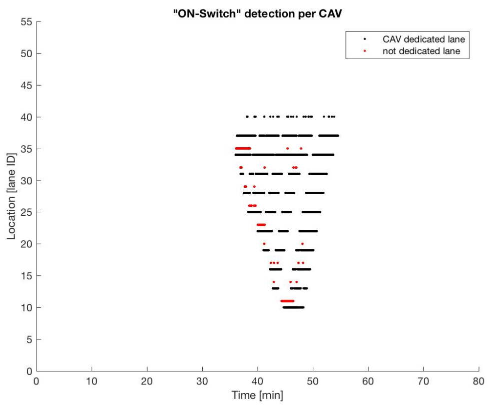
Figure K.3. – The "On-switch" detection plot over location and time. The CAVs in the left (dedicated) lane while the lane is dedicated are black, the CAVs that are not yet on the left lane are red.

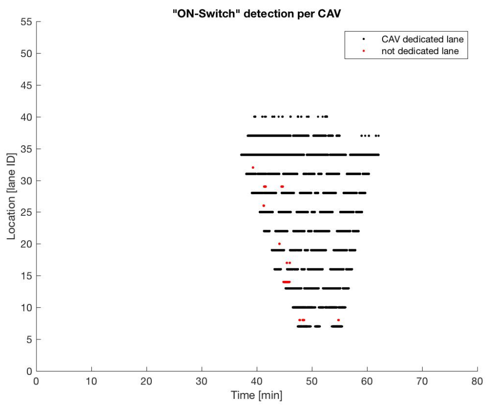
Below in figure K.4 the relevant on-switch detection plots per CAV are depicted. The shape of plots of the strategies differ from each other. It is clearly visible that with the strategy with an one-time density threshold check the left lane stays dedicated ("on") until the tail of the traffic jam has propagated to the last (most upstream) DDLS. At that moment the strategy is gradually (from upstream to downstream) deactivated (turned "off"). In the strategy with a permanent density threshold check strategy remains active for a longer period of time, and gaps in activity can be seen (scenario with 2% CAVs, first from the top). When compared to the speed contour plots, it shows that the strategies work as described in section 3.4. It starts when the designated jam area is congested and it ends when the last DDLS is congested in a consecutive manner.

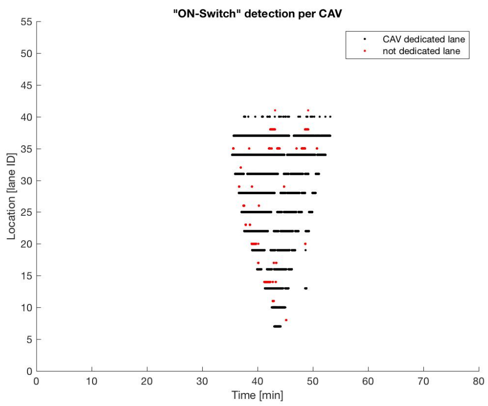
Furthermore the stop time of the strategy, 5 minutes after the peak demand has passed, shows is clearly visible at the one-time strategy with 20% CAVs (4th from the top). Also, this result shows only 1 run, this is therefore just an example. This example identifies some of the operations of the strategies.

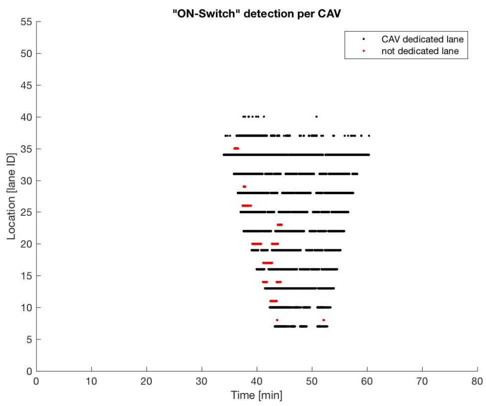

"ON-Switch" detection per CAV
CAV dedicated lane
not dedicated lane
Location [lane ID]
Time [min]


"ON-Switch" detection per CAV
CAV dedicated lane
not dedicated lane
Location [lane ID]
Time [min]


"ON-Switch" detection per CAV
CAV dedicated lane
not dedicated lane
Location [lane ID]
Time [min]


"ON-Switch" detection per CAV
CAV dedicated lane
not dedicated lane
Location [lane ID]
Time [min]


"ON-Switch" detection per CAV
CAV dedicated lane
not dedicated lane
Location [lane ID]
Time [min]


"ON-Switch" detection per CAV
CAV dedicated lane
not dedicated lane
Location [lane ID]
Time [min]

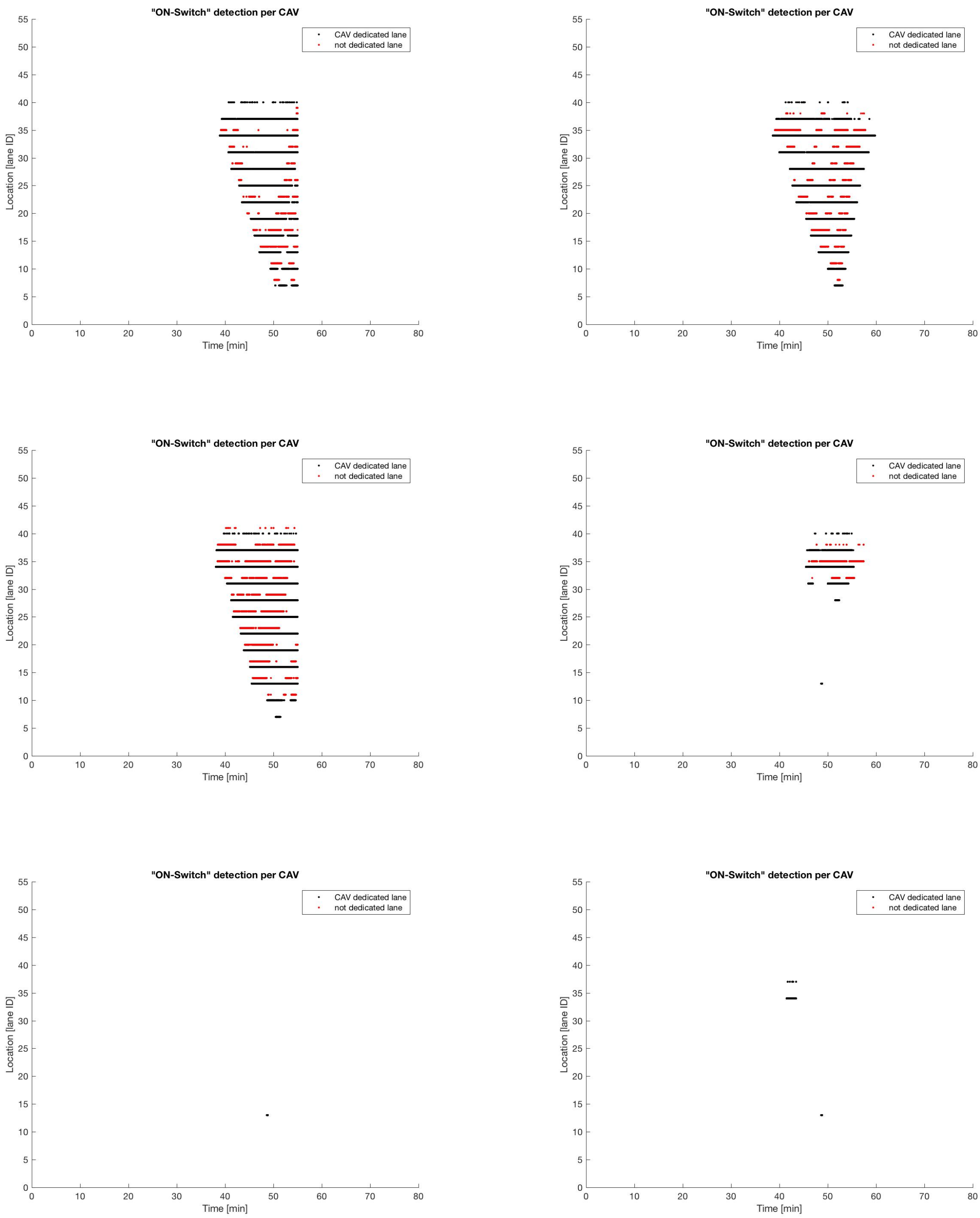


Figure K.4. – All relevant on-switch detection plots (of 12 scenarios). The left column shows the strategy with an one-time density threshold check and the right column shows the strategy with a permanent density threshold check. The six scenarios (the rows) show the penetration rate of the CAVs in a ascending order (from top to bottom: 2%, 5%, 10%, 20%, 30% and 40%).

K.3. Time spent in system (TSiS) per vehicle type

Below in figure K.5 the TSiS plot of the platoon formation strategy with an one-time density threshold check with 5% CAVs is given as an example of the orientation of the TSiS plots in figure K.2.

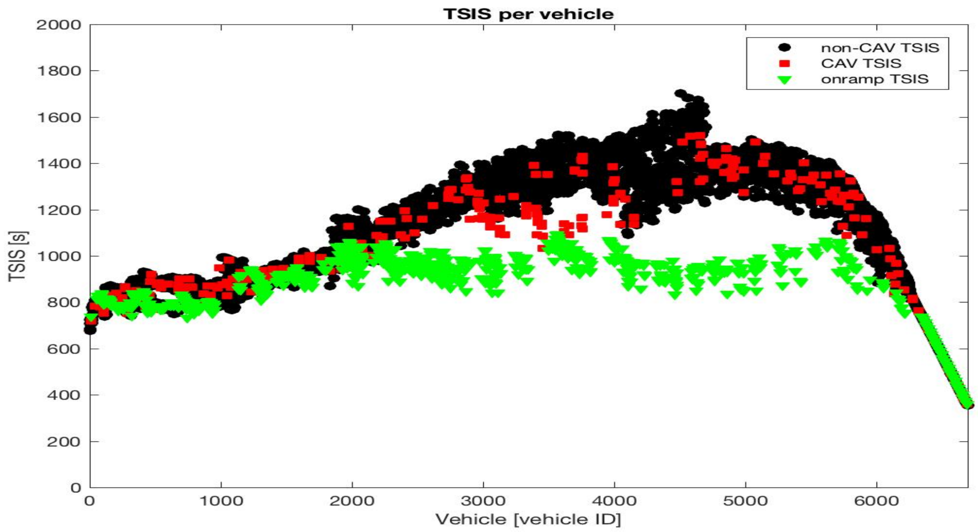
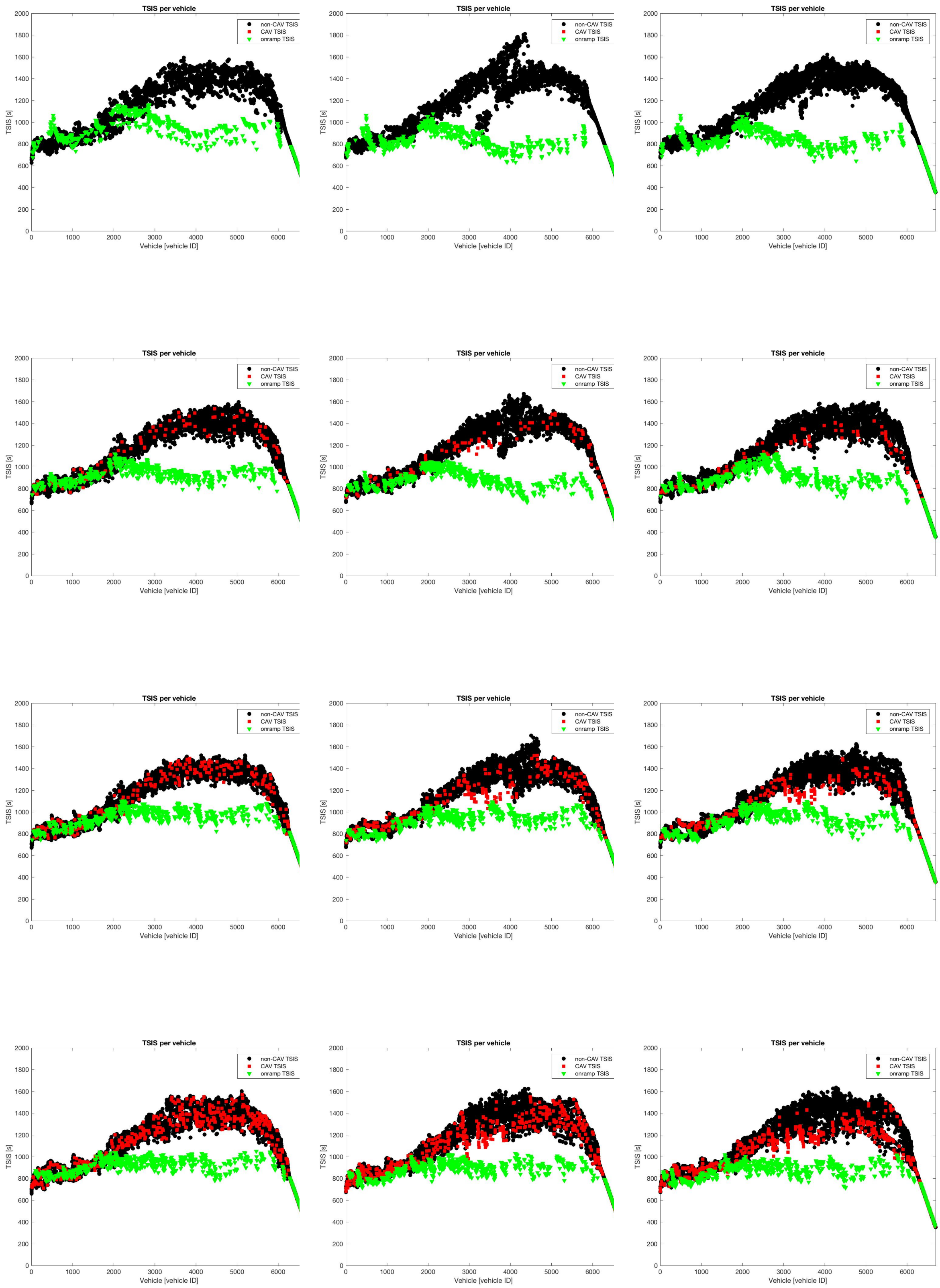


Figure K.5. – The time spend in the system (TSiS) per vehicle. On the y-axis the time spend [s] is given. The x-axis describes vehicle ID. The black dots represent the non-CAVs, the red squares represent the CAVs and the green triangles represent the on-ramp vehicles.


TSIS per vehicle
non-CAV TSIS
CAV TSIS
onramp TSIS
TSIS [s]
Vehicle [vehicle ID]
0
200
400
600
800
1000
1200
1400
1600
1800
2000
1000
2000
3000
4000
5000
6000

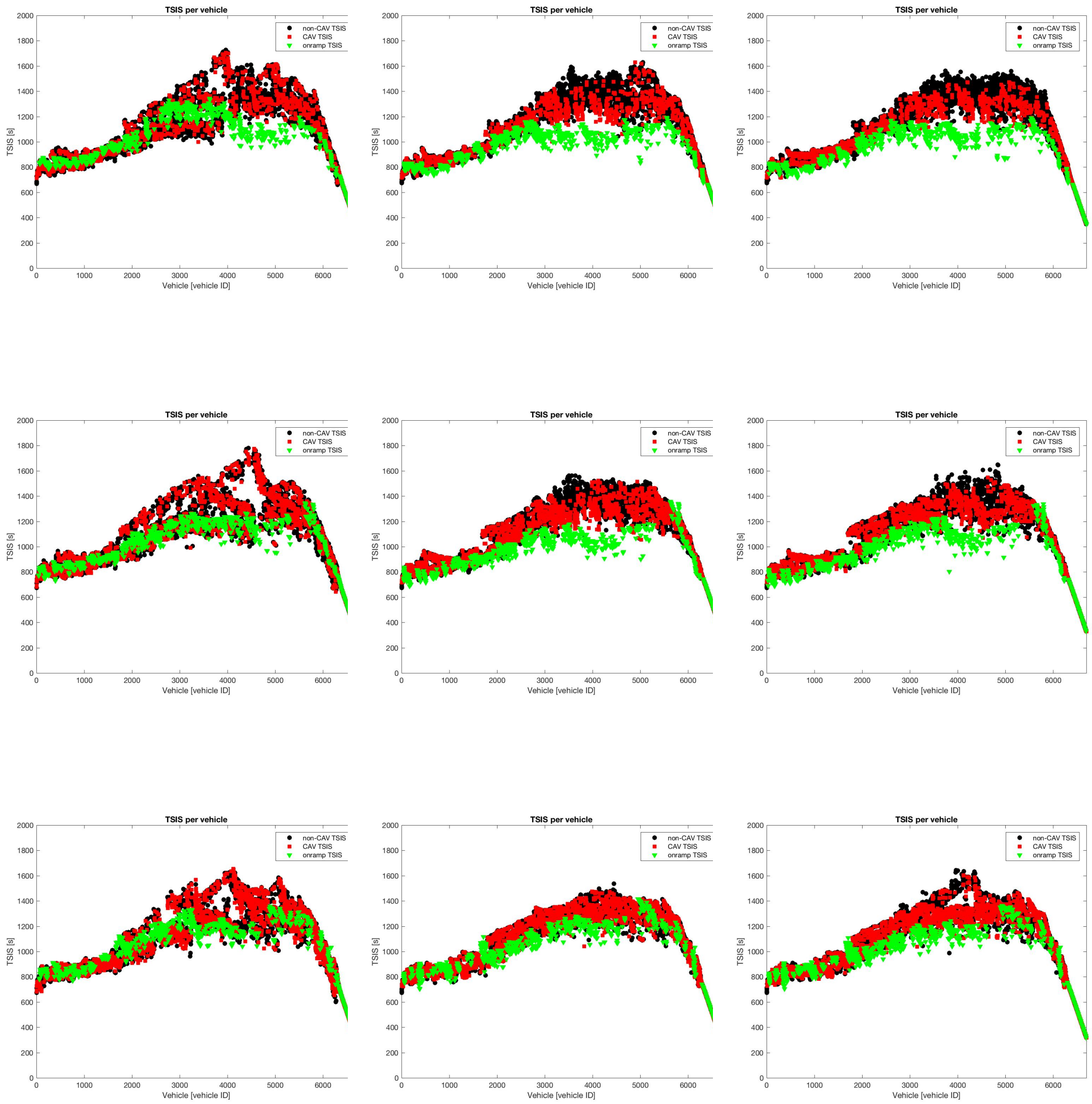


Figure K.6. – The time spent in the system per individual vehicle of all 21 scenarios, the left column shows the base scenario ("no"strategy), the middle column shows the strategy with an one-time density threshold check and the right column shows the strategy with a permanent density threshold check. The seven scenarios (the rows) show the penetration rate of the CAVs in a ascending order (from top to bottom: 0%, 2%, 5%, 10%, 20%, 30% and 40%).

K.4. Bar plots of number of platoon leaders

This section shows all the bar plots of each scenario, indicating the number and size of the platoons formed.

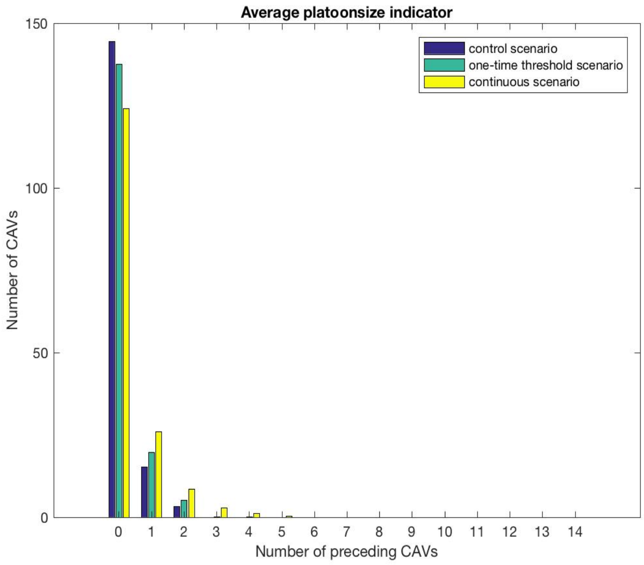


Figure K.7. – bar plot comparison of platoon size, CAV penetration 2%

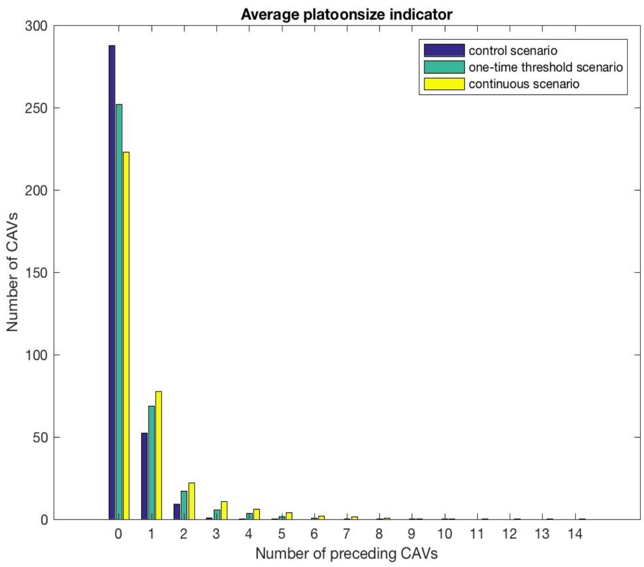


Figure K.8. – bar plot comparison of platoon size, CAV penetration 5%

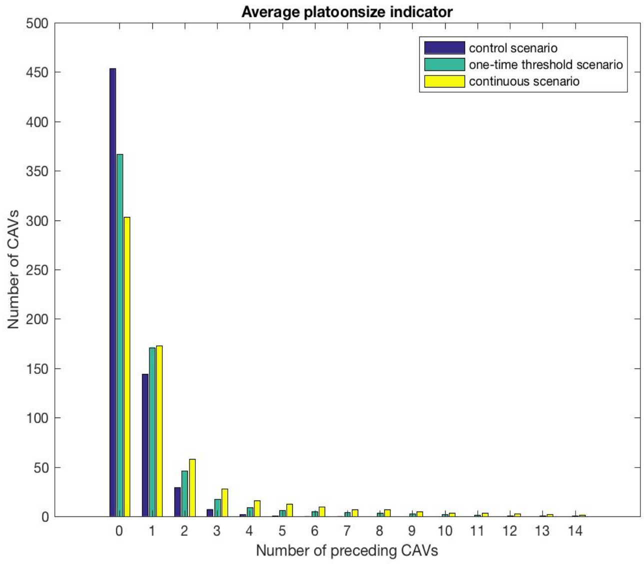


Figure K.9. – bar plot comparison of platoon size, CAV penetration 10%

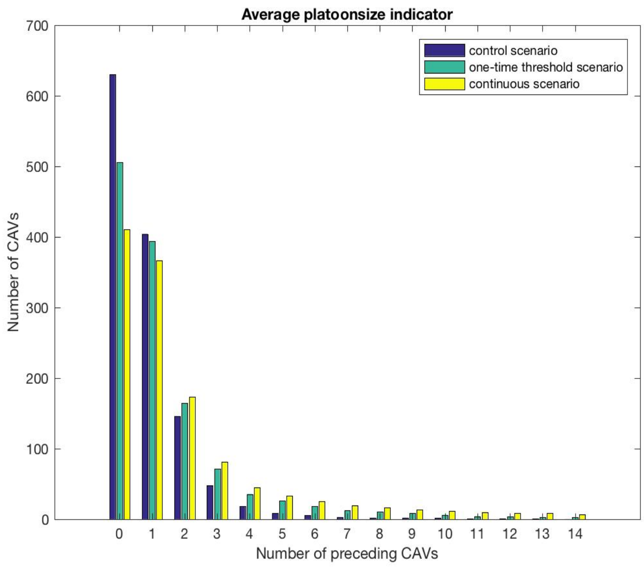


Figure K.10. – bar plot comparison of platoon size, CAV penetration 20%

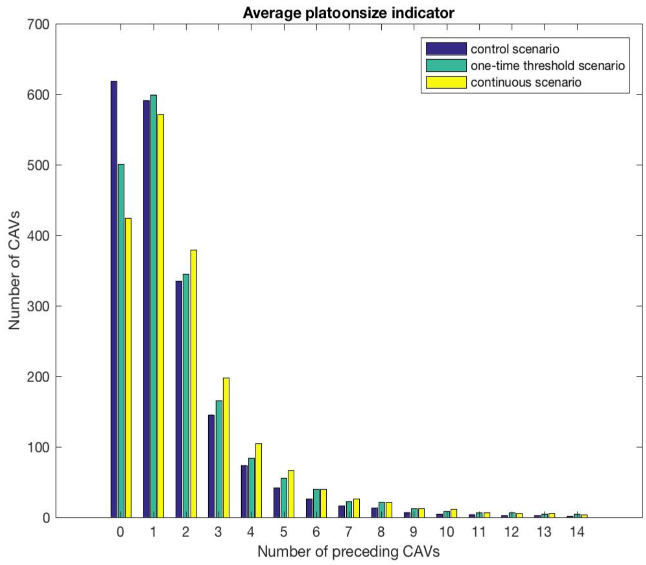


Figure K.11. – bar plot comparison of platoon size, CAV penetration 30%

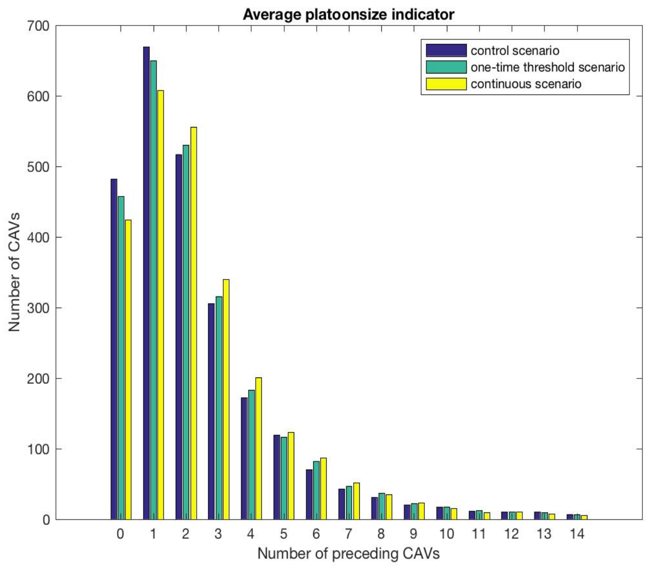


Figure K.12. – bar plot comparison of platoon size, CAV penetration 40%

Appendix L. Matrix sign example

Below a sketch of matrix sign is presented. This is an example of how a matrix sign for a dedicated lane could look like.

Figure L.1. – Example of a matrix sign for DDLSs with CAV only dedication

Appendix M.Confidence intervals

The sample size of the experiment is determined at 6 seeds as is shown in appendix D.1. This appendix shows all of the 95% confidence intervals of every result in this thesis. It presents them consecutively, in the following order:"No strategy", "Strategy with an One-time density threshold check" (indicated as "strat. one.") and "strategy with a permanent density threshold check" (indicated as "strat. perm.").

No Strategy: Total outflow student t-test vs. Penetration level	**Mean**	**Standard deviation**	**95% lower boundary**	**95% upper boundary**
Strat0_pCAV0%	5231	132	5123	5340
Strat0_pCAV2%	5311	106	5224	5398
Strat0_pCAV5%	5396	110	5305	5486
Strat0_pCAV10%	5436	66	5381	5490
Strat0_pCAV20%	5645	55	5600	5690
Strat0_pCAV30%	5793	18	5778	5807
Strat0_pCAV40%	5788	16	5775	5802

No Strategy: TTSiS all veh. student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat0_pCAV0%	6598614	210040	6425826	6771402
Strat0_pCAV2%	6649601	22523	6631073	6668129
Strat0_pCAV5%	6603830	34016	6575847	6631813
Strat0_pCAV10%	6585333	16920	6571414	6599252
Strat0_pCAV20%	6487670	18993	6472046	6503294
Strat0_pCAV30%	6427892	16162	6414596	6441188
Strat0_pCAV40%	6367581	17908	6352849	6382313

No Strategy: TTSiS CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat0_pCAV0%	0	0	0	0
Strat0_pCAV2%	133919	12370	123743	144095
Strat0_pCAV5%	330060	17711	315489	344630
Strat0_pCAV10%	631139	17509	616735	645542
Strat0_pCAV20%	1293011	40566	1259640	1326383
Strat0_pCAV30%	1922684	47272	1883797	1961572
Strat0_pCAV40%	2536775	32330	2510180	2563371

No Strategy: TTSiS non-CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat0_pCAV0%	6598614	210040	6425826	6771402
Strat0_pCAV2%	6515683	17574	6501226	6530139
Strat0_pCAV5%	6273770	39548	6241236	6306305
Strat0_pCAV10%	5954194	34295	5925982	5982407
Strat0_pCAV20%	5194659	30742	5169369	5219948
Strat0_pCAV30%	4505207	59272	4456448	4553967
Strat0_pCAV40%	3830806	30676	3805571	3856040

No Strategy: avg. preceding CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat0_pCAV0%	1.35	0.00	1.35	1.35
Strat0_pCAV2%	1.19	0.02	1.18	1.21
Strat0_pCAV5%	1.45	0.06	1.40	1.50
Strat0_pCAV10%	1.86	0.10	1.78	1.94
Strat0_pCAV20%	2.53	0.25	2.32	2.73
Strat0_pCAV30%	3.00	0.25	2.79	3.20
Strat0_pCAV40%	3.51	0.12	3.41	3.61

No Strategy: Deleted vehicles student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat0_pCAV0%	5.0	0.00	5.00	5.00
Strat0_pCAV2%	5.0	0.00	5.00	5.00
Strat0_pCAV5%	5.0	0.00	5.00	5.00
Strat0_pCAV10%	5.0	0.00	5.00	5.00
Strat0_pCAV20%	21.0	0.00	21.00	21.00
Strat0_pCAV30%	32.2	5.49	27.65	36.68
Strat0_pCAV40%	62.3	3.27	59.65	65.02

Strat. one-time: Total outflow student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	5338	144	5219	5456
Strat1_pCAV2%	5310	90	5236	5384
Strat1_pCAV5%	5379	111	5287	5470
Strat1_pCAV10%	5441	37	5410	5472
Strat1_pCAV20%	5605	126	5502	5708
Strat1_pCAV30%	5789	7	5783	5794
Strat1_pCAV40%	5785	31	5760	5810

Strat. one-time: TTSiS all veh. student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	6629800	81399	6562838	6696762
Strat1_pCAV2%	6657119	14555	6645146	6669093
Strat1_pCAV5%	6611719	29422	6587515	6635923
Strat1_pCAV10%	6592444	17784	6577813	6607074
Strat1_pCAV20%	6538819	24167	6518938	6558699
Strat1_pCAV30%	6458896	29213	6434864	6482927
Strat1_pCAV40%	6412894	9330	6405218	6420569

Strat. one-time: TTSiS CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	0	0	0	0
Strat1_pCAV2%	129281	11375	119923	138638
Strat1_pCAV5%	321331	18450	306153	336508
Strat1_pCAV10%	616988	18152	602056	631920
Strat1_pCAV20%	1274710	41122	1240881	1308539
Strat1_pCAV30%	1917028	51978	1874268	1959787
Strat1_pCAV40%	2557247	28972	2533414	2581081

Strat. one-time: TTSiS non-CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	6629800	81399	6562838	6696762
Strat1_pCAV2%	6527839	21637	6510039	6545638
Strat1_pCAV5%	6290388	33716	6262653	6318124
Strat1_pCAV10%	5975456	29859	5950893	6000018
Strat1_pCAV20%	5264109	25993	5242725	5285492
Strat1_pCAV30%	4541868	74526	4480560	4603176
Strat1_pCAV40%	3855646	29261	3831575	3879718

Strat. one-time: Avg. preceding CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	1.35	0.00	1.35	1.35
Strat1_pCAV2%	1.19	0.02	1.18	1.21
Strat1_pCAV5%	1.45	0.06	1.40	1.50
Strat1_pCAV10%	1.86	0.10	1.78	1.94
Strat1_pCAV20%	2.53	0.25	2.32	2.73
Strat1_pCAV30%	3.00	0.25	2.79	3.20
Strat1_pCAV40%	3.51	0.12	3.41	3.61

Strat. one-time Deleted vehicles student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	5.00	0.00	5.00	5.00
Strat1_pCAV2%	5.00	0.00	5.00	5.00
Strat1_pCAV5%	5.00	0.00	5.00	5.00
Strat1_pCAV10%	5.00	0.00	5.00	5.00
Strat1_pCAV20%	21.00	0.00	21.00	21.00
Strat1_pCAV30%	44.83	2.86	42.48	47.18
Strat1_pCAV40%	67.67	1.03	66.82	68.52

Strat. one-time: Switch-on % student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat1_pCAV0%	0.00	0.00	0.00	0.00
Strat1_pCAV2%	6.73	1.87	5.19	8.28
Strat1_pCAV5%	9.72	1.83	8.21	11.23
Strat1_pCAV10%	9.76	1.11	8.84	10.68
Strat1_pCAV20%	10.94	0.80	10.28	11.60
Strat1_pCAV30%	5.67	6.22	0.55	10.78
Strat1_pCAV40%	2.16	3.40	-0.64	4.95

Strat. permanent: Total outflow student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat2_pCAV0%	5346	145	5227	5466
Strat2_pCAV2%	5316	84	5247	5384
Strat2_pCAV5%	5411	79	5346	5476
Strat2_pCAV10%	5436	49	5395	5476
Strat2_pCAV20%	5582	65	5528	5636
Strat2_pCAV30%	5783	18	5768	5798
Strat2_pCAV40%	5785	37	5755	5815

Strat. permanent: TTSiS all veh. student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat2_pCAV0%	6640841	63988	6588202	6693480
Strat2_pCAV2%	6636448	11263	6627183	6645714
Strat2_pCAV5%	6615592	21690	6597749	6633434
Strat2_pCAV10%	6593773	32506	6567032	6620513
Strat2_pCAV20%	6551832	17410	6537509	6566154
Strat2_pCAV30%	6472124	19556	6456037	6488212
Strat2_pCAV40%	6419967	28430	6396580	6443355

Strat. permanent: TTSiS CAVs student t-test vs. Penetration level	Mean	Standard deviation	95% lower boundary	95% upper boundary
Strat2_pCAV0%	0	0	0	0
Strat2_pCAV2%	128596	10834	119684	137509
Strat2_pCAV5%	315623	17134	301528	329719
Strat2_pCAV10%	608136	23127	589111	627161
Strat2_pCAV20%	1271281	36285	1241431	1301131
Strat2_pCAV30%	1917000	53622	1872889	1961112
Strat2_pCAV40%	2557194	35237	2528207	2586181

Strat. permanent: TTSiS non-CAVs student t-test vs. Penetration level	**Mean**	**Standard deviation**	**95% lower boundary**	**95% upper boundary**
Strat2_pCAV0%	6640841	63988	6588202	6693480
Strat2_pCAV2%	6507852	16955	6493904	6521800
Strat2_pCAV5%	6299968	23880	6280323	6319613
Strat2_pCAV10%	5985637	42604	5950589	6020685
Strat2_pCAV20%	5280550	22432	5262097	5299004
Strat2_pCAV30%	4555124	68149	4499062	4611186
Strat2_pCAV40%	3862774	33666	3835079	3890468

Strat. perm.: Avg. preceding CAVs student t-test vs. Penetration level	**Mean**	**Standard deviation**	**95% lower boundary**	**95% upper boundary**
Strat2_pCAV0%	1.35	0.00	1.35	1.35
Strat2_pCAV2%	1.36	0.05	1.31	1.40
Strat2_pCAV5%	1.72	0.10	1.63	1.80
Strat2_pCAV10%	2.47	0.18	2.32	2.62
Strat2_pCAV20%	3.58	0.43	3.22	3.93
Strat2_pCAV30%	3.17	0.26	2.95	3.38
Strat2_pCAV40%	3.59	0.18	3.44	3.74

Strat. permanent: Deleted Vehicles student t-test vs. Penetration level	**Mean**	**Standard deviation**	**95% lower boundary**	**95% upper boundary**
Strat2_pCAV0%	5.00	0.00	5.00	5.00
Strat2_pCAV2%	5.00	0.00	5.00	5.00
Strat2_pCAV5%	5.00	0.00	5.00	5.00
Strat2_pCAV10%	5.00	0.00	5.00	5.00
Strat2_pCAV20%	21.00	0.00	21.00	21.00
Strat2_pCAV30%	46.00	0.00	46.00	46.00
Strat2_pCAV40%	65.67	1.03	64.82	66.52

Strat. permanent: Switch-On % student t-test vs. Penetration level	**Mean**	**Standard deviation**	**95% lower boundary**	**95% upper boundary**
Strat2_pCAV0%	0	0.00	0	0
Strat2_pCAV2%	19.07	4.40	15.45	22.69
Strat2_pCAV5%	22.63	3.99	19.34	25.91
Strat2_pCAV10%	25.81	4.75	21.90	29.71
Strat2_pCAV20%	21.97	3.06	19.45	24.49
Strat2_pCAV30%	4.95	5.28	0.60	9.30
Strat2_pCAV40%	1.13	1.82	-0.37	2.63