The impact of Connected and Automated Vehicles on highway work zone traffic efficiency and safety

A simulation study

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by

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Preface

Before you lies my thesis on the impacts of connected and automated vehicles on highway work zone traffic efficiency and safety. It is the final piece of my MSc programme Transport, Infrastructure & Logistics at Delft University of Technology. Finalizing this research not only concludes the research that I have been working on for the last months, but it also concludes my time as a student in Delft. It has been an invaluable journey of six years in which I have had the chance to develop myself both on an academic and on a personal level.

Starting my BSc programme in Technology, Policy & Management I never expected that I would later graduate as a civil engineer. Although I always liked technology and innovation, it was the link to people that always fascinated me. Over the years I broadened my scope however, and I discovered my preference for innovative technologies that make our day-to-day lives a little easier and the world a little better. This prompted me to specialize in Transport and Logistics during my BSc programme. A decision that, in hindsight, was a first step towards my current MSc programme in which I studied this domain thoroughly.

This research was executed in collaboration with VolkerWessels and Delft University of Technology. I want to thank VolkerWessels, and especially Brian Kersten and Marit Reinders, for giving me the opportunity to carry out this research on their behalf. When I started my explorative research I had little experience in vehicle automation research. I was however looking for a challenge. They allowed allowed me to formulate my own research that suited their interests, but was also exiting to me. This helped a lot in staying motivated during the whole research process.

It has not been an easy process. After my first week at VolkerWessels, working from home became the norm as a result of the Covid crisis. This posed many challenges, both practically and mentally. Working on a MSc thesis is known to be a lonesome activity. Students are mostly on their own during this process, which makes social interaction all the more important. These interactions were very scarce, which I found more difficult than I could have expected beforehand. With a lot of support from the outside, I am eventually satisfied with the results of my research.

I want to thank again my VolkerWessels supervisors, Brian Kersten and Marit Reinders, for their constant support during my research. Even though most of our contact was digitally, I never felt a distance in our conversations. This made it very easy to ask for input, which they gladly and generously provided. I also want to thank my TU Delft supervisors, Haneen Farah, Jan Anne Annema and Bart van Arem, who were always available to exchange thoughts or to provide new insights. While allowing me the freedom to develop my own research, they showed new possible directions or advice where required.

Finally, I would like to thank my close friends and family who I feel blessed to be surrounded by. I genuinely believe that I could not have done it without you.

Bart van Leeuwen
Maasland, November 2020

Executive summary

Introduction

In recent years, vehicle automation technologies have severely advanced. Connected and automated vehicles(CAVs) show great potential to improve traffic safety and efficiency. CAVs are generally believed to increase traffic safety significantly since most accidents are related to human error, although the magnitude of the reduction varies across literature. If all vehicles on the road would be automated, the traffic efficiency is believed to be the highest as a result of theoretical features such as a smaller headway, more constant driving speed and a quicker reaction time. However, these are effects that are expected when the entire vehicle fleet is fully connected and highly automated. If that point is ever reached, there is a very long transition period in which CAVs and conventional human operated vehicles coexist.

Road operators are starting to realize that there is a need for fitting infrastructure ensuring uninterrupted, predictable, safe and efficient traffic within this transition period. In new EU funded studies high risk scenarios have been formulated where infrastructure is essential. Among these high risk scenarios is the scenario of roadwork zones. A form of guidance, in the form of Infrastructure to vehicle (I2V) communication, enabled by wireless communication networks such as Wifi or 5G (or newer iterations), is one of the alternatives that would make safe en efficient traffic possible (Kulmala et al., 2019, Marshall, 2017). Initial studies focused on this topic have been conducted. These studies conclude that further research is required however. The impact of CAVs on traffic efficiency and safety should be further studied in different work zones in order to formulate feasible communication strategies that could be used as possible solutions. This way work zones can in the future be designed to better suit the traffic properties. The research goals of this study are twofold:

1. To better understand the impacts of CAVs on the traffic efficiency and traffic safety in highway roadwork zones in different scenarios.
2. To make a well formulated estimation of how current communication in work zones will need to be changed in the future.

Methods

Using PTV VISSIM 11, two road configurations were simulated: a two-lane road with a right lane closure, and a two lane road with a 3-1 contraflow system implemented in them. Three types of CAVs were simulated to account for the uncertainties of how CAVs will develop in the future. These were the *cautious* driving logic, the *normal* driving logic and the *all knowing* driving logic. The *cautious* driving logic was formulated in such a way that the vehicle never risks an accident. The *normal* driving logic was formulated to emulate human driving behaviour with the added capacity of measuring distances and speeds of other vehicles via sensors. The *all knowing* driving logic was fully aware of all its surroundings and used this knowledge to have the best possible performances within the bounds of safety. These CAVs were all simulated at 5 different penetration rates (from 0% to 100%, in steps of 25%) in combination with conventional(i.e. human operated) vehicles. In order to assess what road authorities can do to increase future traffic efficiency and traffic safety, communication strategies were implemented for CAVs based on the earlier simulation outcomes. In total, this led to 50 different configurations to simulate. The model was validated by comparing the results to the outcomes of comparable simulation studies.

Conclusions

The results showed that if CAVs are programmed to be too conservative when they are introduced on a larger scale without modification to the infrastructure, leads to major traffic efficiency drops in

work zones. This leads to large travel times, but could potentially also lead to dangerous situations. The extent to which this happens is however very dependent on the driving behaviour of conventional vehicles as well. Additionally, it showed that CAVs with more aggressive behaviour, such as the all knowing CAVs, could lead to safety issues for conventional drivers since these vehicles take risks that would in reality not be possible. Simulations do not simulate accidents, but it is very likely that these would occur because of interactions between aggressive CAVs and conventional drivers.

Results showed that if an early merging communication strategy is implemented as an addition to the conventional means of communication, this results in an increase in traffic efficiency and safety. These results are not directly suited for extrapolation toward real-life traffic situations however. The robustness of this measure should first be tested extensively with other traffic compositions and driving behaviours before physical tests can be applied. Also this conclusion only holds for lower penetration rates of CAVs. At higher rates, the effects of communication are nullified. The communication of a longer headway to the more aggressive CAVs showed potential to increase safety, although increasing the headway alone is likely not enough to ensure safety. These more aggressive CAVs still tend to accelerate/decelerate harder than usual which could in reality lead to problems.

Recommendations

Current new vehicles are equipped with level 2 vehicle automation systems. These vehicles rely on sensors while driving that can have issues reading the roads within complex road work zones. The first actions by road work companies should not be aimed at making it possible for these vehicles to drive through the work zones, but should warn the vehicle owners that their vehicle is not able to drive through the current work zones by placing prohibition sign such as figure 2. When CAVs reach level 3, actions should be taken to make it possible for CAVs to drive through simple work zones. This can be done by designing these simple work zones with capabilities of CAVs in mind. Important infrastructural aspects are the visibility, consistency and quality of the road, road markings, traffic signs etc. For lower levels of CAVs physical infrastructure elements are more important than digital elements. Digital elements such as a digital map, GPS and traffic management can however already be utilized to increase information both CAVs and CVs can use. In complex work zones, where the road design cannot suit the need of CAVs, drivers should be obliged to take over control to ensure traffic safety. To communicate this obligation to the vehicle operators, signs such as figure 2 should still be introduced and installed.

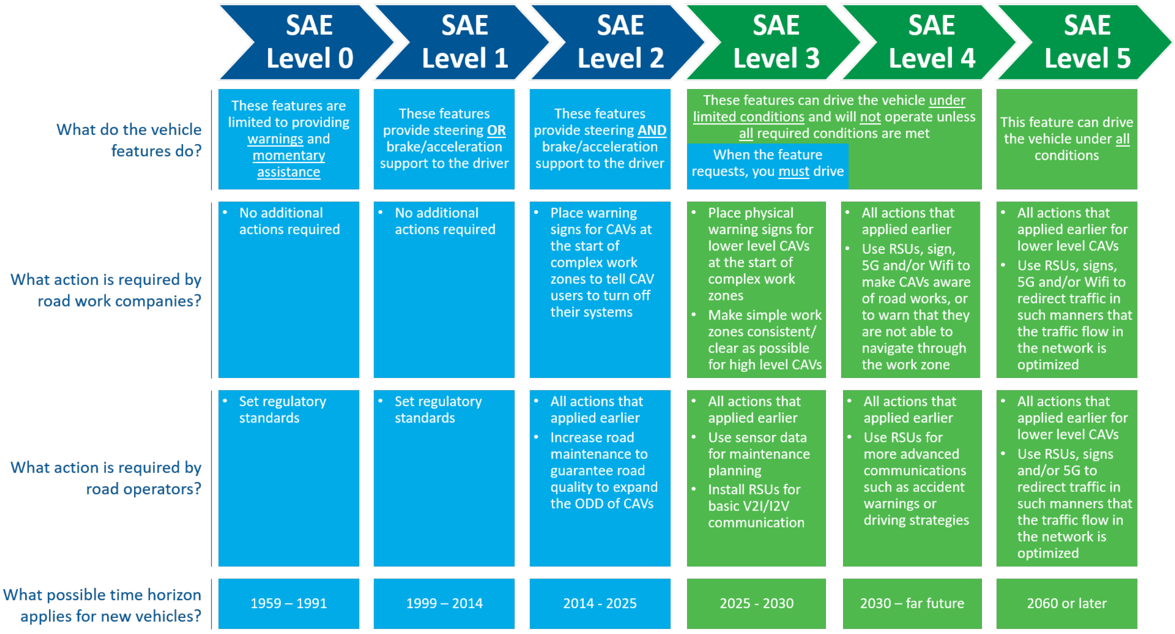
As CAVs become more advanced, new use can be made of smart infrastructure that will likely become more common by this time, such as road side units (RSUs), 5G (or newer versions), or Wifi. For level 4 CAVs this communication can be used to communicate information to make it possible for the vehicle to move safely through the work zone, or to make them aware that the work zone is still too complex. For level 5 CAVs, the communication can be used exclusively to optimize traffic efficiency and safety.

It is currently too early for road work companies to start applying large scale communication strategies aimed at CAVs since the CAV fleet is simply too small. Connectivity in vehicles is a development that transcends automated driving however. Communication strategies aimed at conventional vehicles could be effective as well when the infrastructure and the vehicles are able to communicate. More research into these strategies is required. It is good for road work companies to be aware of the potential future developments that are possible as CAVs increase in number. If these vehicles are designed to be very cautious, communication can lead to the relieving of congestion and to the increasing of safety. More research into these fields is still required however, before large steps are taken.

Road operators have to act in an earlier stage, possibly at this moment. Newly introduced systems require new regulatory standards. These should be formulated proactively, so that the innovations can be controlled better. Now that level 2 automation systems become more prevalent, the roads will need to be maintained better to expand the ODD of CAVs. This includes ensuring the visibility, consistency and quality of the road, road markings, traffic signs etc. It also includes keeping in mind the effects of road curvature and lane width on the functioning of CAVs. The sensors in CAVs can also be used as an opportunity. The sensor data could be used by road operators to obtain a real-time image of the state of the road markings and signs to optimize road maintenance.

Road authorities should consider to begin installing road side units (RSUs) for digital communication to connected vehicles. Connectivity in vehicles is a development that transcends automated driving. For conventional vehicles RSUs are an addition to provide road users with real time information, but for CAVs it will become an essential part of the digital infrastructure. RSUs can be used to warn oncoming traffic, to redirect traffic or to make optimal use of the traffic network by optimizing vehicle routes. This study showed two possible applications of RSUs but numerous other applications could be devised.

In conclusion, road operators should include connected and automated vehicles in their infrastructure policy. To facilitate a transition toward automated driving the role of infrastructure is very important. This should be reflected in the policies that are formed. Currently this is not always the case, but there are studies taking place commissioned by the Dutch government regarding this topic. As future vehicles continue to get smarter, there will still be need for human intervention to account for unforeseen irregularities. *"We will always need the human in the loop"* - Maarten Sierhuis, Nissan Silicon Valley Chief Technology Director (Marshall, 2017).



	SAE Level 0	SAE Level 1	SAE Level 2	SAE Level 3	SAE Level 4	SAE Level 5
What do the vehicle features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met When the feature requests, you must drive		This feature can drive the vehicle under all conditions
What action is required by road work companies?	• No additional actions required	• No additional actions required	• Place warning signs for CAVs at the start of complex work zones to tell CAV users to turn off their systems	• Place physical warning signs for lower level CAVs at the start of complex work zones • Make simple work zones consistent/ clear as possible for high level CAVs	• All actions that applied earlier • Use RSUs, sign, 5G and/or Wifi to make CAVs aware of road works, or to warn that they are not able to navigate through the work zone	• All actions that applied earlier for lower level CAVs • Use RSUs, signs, 5G and/or Wifi to redirect traffic in such manners that the traffic flow in the network is optimized
What action is required by road operators?	• Set regulatory standards	• Set regulatory standards	• All actions that applied earlier • Increase road maintenance to guarantee road quality to expand the ODD of CAVs	• All actions that applied earlier • Use sensor data for maintenance planning • Install RSUs for basic V2I/I2V communication	• All actions that applied earlier • Use RSUs for more advanced communications such as accident warnings or driving strategies	• All actions that applied earlier for lower level CAVs • Use RSUs, signs and/or 5G to redirect traffic in such manners that the traffic flow in the network is optimized
What possible time horizon applies for new vehicles?	1959 – 1991	1999 – 2014	2014 - 2025	2025 - 2030	2030 – far future	2060 or later

Figure 1: Timeline of action that should be considered by road work companies and road operators at different automations levels (Adated from SAE J3016 (SAE International, 2018), time horizons based on (Smarttransport, 2020, Smith et al., 2017, van Asselt, 2019))

Figure 2: Prohibition sign

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Introduction

In recent years, vehicle automation technologies have significantly advanced. Car manufacturers already equip their new models with automated functionalities. The features vary from self-parking software to crash avoidance systems such as automated braking, lane departure warning systems and forward collision warning systems. As these technologies become more common, countries start taking their own steps to get ahead in knowing what is to be expected of these technologies. In this light AV testing has been legalized in several different parts of the world including the US, Austria, Australia and China (Morando et al., 2018).

The large interest from governmental agencies in these new technologies is for good reason. In the Netherlands alone, the number of traffic fatalities that are suffered every year has remained constant in the last two decades. Opposite to this, the Dutch government and the European Union have set the goal of 0 traffic fatalities in the year 2050 (van Asselt, 2019). Automated vehicles(AVs) are generally believed to increase traffic safety significantly since most accidents are related to human error, although the magnitude of the reduction varies across literature (Chan, 2017, Shladover, 2009).

Traffic efficiency is expected to benefit from vehicle automation as well. This is the extent to which a traffic system can meet the travel demand of people in that system (Gaitanidou and Bekiaris, 2012). If all vehicles on the road would be automated, the traffic efficiency is believed to be the highest (Calvert et al., 2017, Liu and Fan, 2020, Mehr and Horowitz, 2020, Penttinen et al., 2019). This is the result of theoretical features such as a smaller headway, more constant driving speed and a quicker reaction time.

With the introduction of such a promising new technology, new issues always arise. Especially in the long transition period in which AVs and conventional human road users use the roads alongside each other, AVs do not naturally improve safety directly. Numerous accidents have occurred already in which the automated driving system(ADS) was found to be active (Green, 2020, Gärtner, 2020, Lambert, 2019). These accidents also led to fatalities. Moreover, when Robocar was initially released in California human drivers remarkably often rear-ended these vehicles at intersections because these automated vehicles tended to brake harder than a human driver would (Stewart, 2018).

Road operators are starting to realize that there is a need for adaptations to the infrastructure ensuring uninterrupted, predictable, safe and efficient traffic in the transition period where AVs and conventional traffic coexists as well. EU funded projects such as INFRAMIX (Berrazouane et al., 2019, Carreras et al., 2018, Erhart et al., 2019, Lytrivis et al., 2018a,b, Markantonakis et al., 2019) and MANTRA (Aigner et al., 2019, Penttinen et al., 2019, Ulrich et al., 2020, van der Tuin et al., 2020a,b) have emerged to research the changes that are needed for traffic to function properly in the period where both AVs and conventional vehicles are present in the vehicle fleet. In their studies high risk scenarios have been formulated. These scenarios have such different characteristics from a normal traffic situation, that additional risks are expected. Among these high risk scenarios is the scenario of roadwork zones. Nissan Silicon Valley Chief Technology Director Maarten Sierhuis stated in an interview that automated vehicles will always need a human in the loop for them to be able to move through such difficult environments (Marshall, 2017). Infrastructure to vehicle (I2V) communication, enabled by wireless communication networks such as Wifi or 5G (or newer iterations), is suggested as a means to make safe en efficient traffic possible (Kulmala et al., 2019, Marshall, 2017).

For the AVs to be able to receive a signal they need to be connected. These Connected and Automated Vehicles(CAVs) are relatively new in the research environment. Lytrivis et al. (2018a), Wen (2018) and van der Tuin et al. (2020b) studied possible ways to influence the traffic efficiency and safety in work zones with different strategies of communication. Lytrivis et al. (2018a) conducted a uses case based analysis to identify challenges for CAVs and to provide solutions to these challenges. Several use cases were dedicated to roadwork zones. It was however identified that due to a lack of insight into automated vehicle behaviour feasible solutions were hard to formulate. More insight into this behaviour is thus required. Wen (2018) executed microscopic simulations in work zones to make travel time predictions. The study simulated one work zone type with 100% CAVs penetration rate. More work zones and different penetrations rates should be simulated to gain a better understanding of the impacts of CAVs. van der Tuin et al. (2020b) simulated two different moving work zones at different penetration rates of CAVs (0-100% with steps of 25%). In these moving work zone simulations, one type of CAV driving behaviour was simulated and an early merging strategy was communicated exclusively to CAVs. The study concludes by stating that more work zones should be studied and that additional communication strategies should be examined.

Based on the recommendations of these earlier studies, this study examines the impacts of three CAV driving behaviours at five penetration rates in two static work zones on traffic efficiency and safety. Based on the first observations, two new communication strategies are tested in these work zones to improve the traffic performance.

1.1. Research objectives and research questions

This research uses microscopic simulation to estimate the effects CAVs will have on the traffic efficiency and traffic safety in highway roadwork zones. Traffic efficiency is explained in this research as the extent to which a traffic system can meet the travel demand of people in that system (Gaitanidou and Bekiaris, 2012). Additionally, two communication strategies will be applied in this model to improve the traffic performance. This will further be discussed in chapter 4. The research goals of this study are twofold:

1. To better understand the impacts of CAVs on the traffic efficiency and traffic safety in highway roadwork zones in different scenarios.
2. To make a well formulated estimation of how current communication in work zones will need to be changed in the future.

These goals will be achieved by looking at the impacts of different CAV penetration rates, different CAV driving behaviour, different work zone layouts and different communication strategies. By doing so a better understanding is gained about what the interactions that take place in traffic and what impacts these interactions have. In order to reach these goals, a main research question has been formulated. This question is:

What are the effects of Connected and Automated Vehicles on the traffic efficiency and traffic safety in highway work zones in the Netherlands?

In order to properly structure the simulation research that will follow, this main research question is separated into several sub-questions. This leads to a better structured and more logical research. Four sub-questions were formulated:

1. *What are the effects of different CAV driving behaviour on traffic efficiency and traffic safety in current highway work zone configurations?*
   Varying driving behaviour logic has been formulated for CAVs (cautious, normal and all knowing) in literature. This behaviour is formulated by a set of parameters. This sub-question aims to find what the effects of the varying CAV types are in order to find behavioural patterns.

2. *What are the effects of CAV penetration rates on traffic efficiency and traffic safety in current highway work zone configurations?*
   It can be expected that different penetration rates of CAVs will haven different effects on the traffic performance. The effects on the traffic performance of conventional vehicles will probably be different for different CAV types and penetration rates. The penetration rates of CAVs are varied to look at these effects on efficiency and safety.
3. *What are promising communication strategies to increase traffic efficiency and traffic safety in highway work zones with CAVs in combination conventional traffic?*
   One of the main research gaps that was identified in chapter 3 was the lack of understanding of the effects of different communication strategies on traffic performance. This question is formulated to find what promising strategies can be identified.
4. *What are the effects of these communication strategies with different CAV driving behaviour, at different penetration rates in different highway work zone configurations on traffic efficiency and traffic safety?*
   The final research question is a synthesis of the steps that came before. In this sub-question the effects of the different communication strategies are explored and experiments including different combinations of parameters are conducted. The goal of this question is to find out what communication strategies work under which circumstances. This allows us to assess the effects of different conditions more in depth, and gain a better understanding of the factors that contribute to the traffic performance with CAVs.

1.2. Research scope

Connected and automated driving is an area of research that is relatively new and that contains a lot of uncertainties. Not all these uncertainties can be studied in this research. Therefore some of these uncertainties will be dealt with by making assumptions, and others will be left out of scope entirely.

The traffic area that is studied is highway work zones in the Netherlands. Highways are expected to be one of the first traffic areas where CAVs will function based on the ODD requirements (Zwijnenberg, 2018). Secondly, it was found that work zones cause many difficulties for CAVs due to the many irregularities around the work zone. Many interaction effects between the CAV and the work zone infrastructure are still unknown or uncertain. These effects are treated in the literature review (chapter 3) but are out of scope for the simulation portion of this research. It is therefore assumed that the vehicle is able to interpret the work zone correctly. This means that effects of take-over requests are out of scope. What is studied, is how the CAVs interact with other traffic and how the CAV driving behaviour influences the traffic performance with different communication strategies. Thirdly, the decision to limit this research to the Dutch highway situation was made because earlier CAV research used this scope as well. This allows for model validation based on findings in those studies. This is necessary since no empirical data on large penetration rates of CAVs is available.

Because the focus of this study lies on the transition period where CAVs are gradually introduced, the penetration rates of CAVs are not fixed. The penetration rate of CAVs is increased throughout the experiments. This study does not focus on a specific level of vehicle or infrastructure automation as formulated by the SAE or ISAD automation levels (Carreras et al., 2018, SAE International, 2018). The difference between CVs and CAVs, as well as the level of automation of the CAVs is determined by their simulated driving logic. This driving logic will differ from the driving logic that CVs use. The same holds for the automation of the infrastructure. The level of automation will be defined by the communication strategy used in the simulations. While drawing conclusions based on the results the link will be made to both classifications for automated driving.

Transportation modeling research can be executed at three main levels. These levels are macroscopic, mesoscopic and microscopic simulation (Barceló, 2010). The levels determine the scale at which the researcher looks at traffic. The first two models look at strategic and tactical decision making in traffic. This includes factors such as the choice to travel, mode choice, route choice and trip distribution. Neither of these two modeling scales are explicitly applied in this study. The focus of this study is on individual vehicle behaviour at an operational level. Microscopic simulation is therefore applied.

1.3. Research framework

The structure of this research is represented in the research framework. As identified by Barceló (2010), a simulation study usually follows the same steps. An adapted version of these steps are presented in figure 1.1. This model shows how this study is built up. First, the literature study provides the information needed for the system analysis. Although some of the literature consists of empirical studies that represent the real traffic system, this study does not use the real system for the system analysis. This box and arrow are therefore represented differently. The gathered information is combined to form a conceptual model of the traffic system in the context of automated driving. This conceptual model is then used as a basis for the simulation model. The translation of the conceptual model into the simulation model is executed in the simulation design step. A very limited calibration is executed. The simulation model is then used to conduct experiments to gather simulation results. These results are subsequently compared to the literature and discussed to interpret them in the broader context of automation research in work zones. Finally the conclusions and recommendations are formulated based upon the interpretations. These recommendations hold relation to the real system, but are not implemented within the system directly as part of this study.

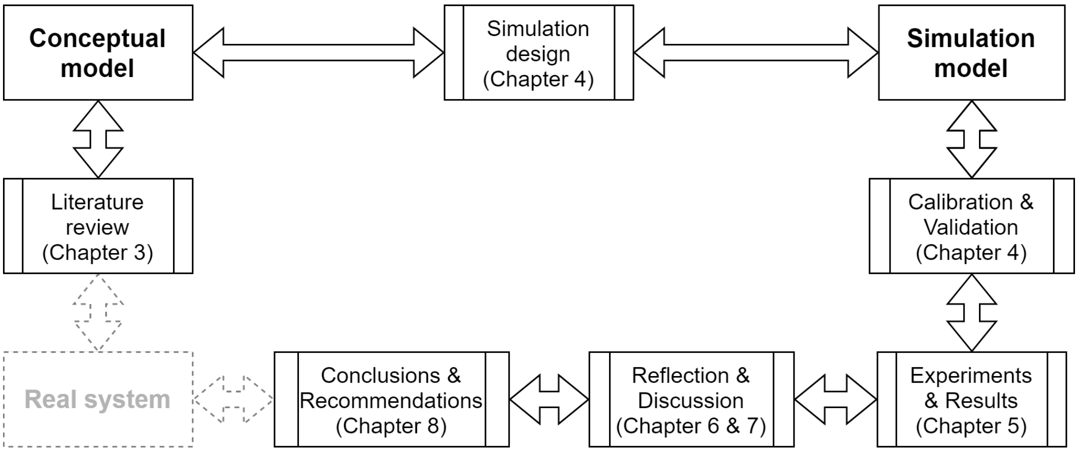


Figure 1.1: Research framework (adapted from Barceló (2010))

1.4. Expected contributions

The expected research contributions of this study are presented in figure 1.2. The figure is divided into four sections. The left part of the figure presents the state of the art and the expected research contributions from a scientific point of view. The right side presents the state of the art and the expected contributions that can be applied in practice. Most factors is the figure are in line with the research gaps that were described earlier this chapter.

The scientific research contributions that are expected consist of four main contributions. These are related to the effects of CAVs in work zones at different penetration rates, the effects of different CAV driving logic and the effects of different communication strategies. These effects are related to traffic safety and traffic efficiency. The contributions that can be expected are limited to those factors that can be studies using a simulation method. Additional research gaps were found related to the effects of road curvature, lane width, road markings and more. Research gaps related to such physical infrastructural elements can not be studied with microscopic simulation however.

The practical contributions that are mentioned in figure 1.2 are mainly aimed at changing the way in which road operators and road work companies design their roads and work zones. Currently CAVs are not a part of the design process of new roads and work zones, and are thus fully aimed at the human drivers. It is expected that this study is able to give recommendations related to how roads and work zones can be designed to suit the needs of CAVs better, and to increase the performance of CAVs. These recommendations can be based both on the literature study and the simulations.

	Scientific	**Practical**
State of the art	• Effects of CAVs in work zones are uncertain; • Effects of different CAV driving logic is unknow; • Effects of communication strategies in combination with different behaviour is unknown.	• Work zones are designed based on Human Factors; • Communication to vehicles is based on Human Factors; • CAVs are not taken into consideration in design decisions; • No general roadmap is available that outlines initial actions to be taken by road operators and road work companies.
Research contributions	• Better understanding of CAVs in workzones at different penetration rates is gained; • Effects of different CAV driving logic is more clear; • Effects of communication strategies are more clear; • New communication strategies are tested.	• Work zones are designed with CAV requirements in mind; • Communication is done both digitally and Human Factor based to benefit both human drivers and CAVs; • CAVs are incorporated in the design decisions; • A general roadmap that outlines initial actions to be taken by road operators and road work companies.

Figure 1.2: Overview of expected practical and scientific contributions

1.5. Reading guide

The remainder of this study is built up as follows. Chapter 2 presents the methodology that was used for this study. Chapter 3 presents the literature review that was conducted to obtain background information and to formulate a conceptual model. Chapter 4 presents how the simulations were formulated based on the findings of the literature review. Chapter 5 presents the results of the experiments that were conducted with the simulations. Chapter 6 reflects on these results by comparing the outcomes to other studies that conducted similar simulation research. Chapter 7 presents the limitations of this study and discusses the results in the light of these limitations, after which chapter 8 presents the conclusions based on the results and the recommendations.

2

Methodology

To answer the research questions that were formulated, several steps were gone through. These steps are briefly described in this chapter. Globally the research process can be divided into two research methods:

1. Literature study
2. Simulation

The literature study was used in preparation of the microscopic simulation. Literature was used to form a conceptual model that represents the traffic system and the relevant factor that were taken into account in the simulations. With simulation this conceptual model was then translated to a traffic model.

2.1. Literature study

The literature study serves two purposes. Firstly the literature study was used to find gaps in the scientific body of knowledge, within the field of automated vehicles. Secondly, it was used to construct a conceptual model of this same area of interest. Validation for the use of a literature study for explorative goals can be found in the fact that a lot of research is available focusing on the impacts of vehicle automation on the traffic performance. Studies that describe possible alternatives to improve this performance in detail are less prevalent, but the conceptual studies that have been conducted provide sufficient background to build upon.

The literature study made use of four different channels to find literature. These were Web of Science, SCOPUS, Google Scholar and TRID. The first three of these channels are general scientific literature databases. TRID is a scientific database with a special focus on transportation research (Avni et al., 2015). Web of Science, SCOPUS and Google Scholar have the advantage that the available body of knowledge is a lot larger than that of TRID. This is also a weakness of the databases however seeing that this leads to a lot of noise in search results. TRID is much more specific but contains less information in general. During the literature study well known search techniques were used such as forward/backward snowballing (Jalali and Wohlin, 2012), as well as manual search techniques to gather enough different sources.

2.2. Simulation

The three most important methods that are used in vehicle automation research are empirical analysis, field operational tests and driving simulation methods. Empirical analysis refers to analyzing a situation that is already in place on current roads. Seeing that this is not the case with automated vehicles, this method can not be used. Field operational tests are specific tests performed in controlled situations in real life environments. The main downsides of these types of tests are that they are expensive to carry out, and that they still yield only a limited amount of data. This method is therefore also not feasible to use. The third method that can be used to answer the research questions is the simulation approach. Simulations are cheap to carry out and they allow for iterative changes to the test environment. Because

CAVs are not deployed on a large scale in practice yet, this testing is very important. Nearly all current studies regarding the quantification of traffic efficiency use some form of traffic simulation (Penttinen et al., 2019). Because simulation requires less resources than field operational testing, and because the time-frame of this study is limited, the decision was made to use a simulation approach to answer the research questions in this study.

The simulations can be executed using three different methods that simulate the traffic environment at three different levels of detail. These methods are macroscopic, microscopic and mesoscopic modeling. Macroscopic modeling simulates traffic from a fully aggregated point of view based on continuum traffic flow theory (Barceló, 2010, Knoop et al., 2019). The objective of this simulation method is to describe the evolution over time of the variables characterizing the macroscopic flows. These variables include factors such as volume, speed and density. Macroscopic modeling also often models traffic over a longer simulation period to look for abstract patterns in traffic. Microscopic modeling simulates the traffic system from a fully disaggregated point of view, describing the fluid process of the dynamics of the individual vehicles in it (Barceló, 2010, Knoop et al., 2019). This includes actions of individual vehicles in response to the surrounding traffic. The objective of this simulation method is to describe the individual interactions between vehicles that take place. This involves actions such as accelerations, decelerations and lane changes. This requires a much more detailed traffic model, comprised of smaller models (e.g. car following model, lane changing model, lateral behaviour model). Mesoscopic modeling combines in a way the microscopic and macroscopic aspects of traffic models (Barceló, 2010, Knoop et al., 2019). The level of detail that is achieved therefore lies between these two methods. There a two main approaches take can be taken in mesoscopic modeling. The first approach, that leans more towards microscopic modeling, does not take individual vehicles into account, but packs these into packages of vehicles that travel between nodes. The second approach, that leans more towards macroscopic modeling, models the aggregated traffic flow dynamics, but bases these on the simplified dynamics of individual vehicles for more detail. Because the main focus in this study lies on the interactions that take place between individual vehicles in traffic, microscopic simulation was found to be the best suited simulation method to use.

There are ample examples of software packages that can be used to construct a microscopic traffic model. Examples of these software packages are AVENUE, SUMO, MITSIM and VISSIM. These traffic flow simulators only contain the software including the mathematical models to run traffic flow models. No specific data or additional tools, such as the driving behaviour parameters, are present within the software. This data has to be implemented by the modeler. Studies by Olstam and Johansson (2018) and Sunkennik et al. (2018), as part of the EU funded CoEXist project in collaboration with PTV, constructed a formulation for the driving behaviour of CAVs in VISSIM 11 and VISSIM 20. Other software packages do not have a formulation for CAV driving behaviour available yet. Other research studying the effects of CAVs by van der Tuin et al. (2020b) used VISSIM as their modeling tool, in part because of this specific CAV driving behaviour formulation. Our research, in part, elaborates upon this research. The VISSIM software is very suited to reach the goals of this study, seeing that it is one of the major commercial microscopic modeling tools available. The decision was therefore made to use the VISSIM 11 software package, that could be obtained through Delft University of Technology, to conduct the traffic simulations needed to answer the research questions.

In the simulations two road configurations were simulated. These were a right lane closure, and a 3-1 contraflow system. Three types of connected and automated vehicles were simulated. These CAVs were all three simulated at 5 different penetration rates (from 0% to 100%, in steps of 25%). Conventional vehicles were simulated with only one type of passenger vehicle. In order to assess what road authorities can do to increase future traffic efficiency and traffic safety, communication strategies were implemented for CAVs based on the earlier simulation outcomes. In total, this led to 50 different configurations to simulate. Every configuration was run 11 times to account for the randomness in driving behaviour. A detailed description of all these different factors and the scenarios is presented in chapter 4.

The purpose of validation testing is to check whether the model functions as it is intended to (Knoop et al., 2019). It is executed to determine if the model is suited to simulate the cases that are under investigation. For the validation to be properly done, the goal of the model should be determined, together with the validity range. The goal of a model can vary a lot and is linked to the validity range. The validity range is formed by the conditions under which the model should function. This range is formed by the scope of the research and the assumptions that come with this. The scope of the model, as well as the assumptions and decision made while building it are stated in chapter 4.

There are many techniques that can be used. One technique is taking real-world data, and compare the model outcome to the empirical data to see if the two align. This will not be possible however in this research, since there are no real-world examples of motorways where high level automated vehicles are part of everyday traffic. A second method that is often used in validation is a sensitivity analysis. In such an analysis individual parameters for which assumptions are made are fluctuated to see what the effects are on the outcomes. In this study this would result in a colossal sensitivity analysis, since many assumptions are made regarding the driving behaviour alone. This behaviour is built up out of many individual parameters, and that would only be one part of the whole sensitivity analysis. Conducting a full sensitivity analysis would therefore be too much work for the limited time-frame of this study. A third method that could be used is to conduct expert validation interviews. The model and its outcomes are then presented to experts in the field that is studied, and they can judge the validity of the model. The advantage of this validation method is that the interpretation is made by someone who has a lot of knowledge in the field of research. A downside is that experts have to be found that are willing to take part in these validation interviews. Another downside is that with these interviews only the opinion of one person is included. It might be the opinion of an expert, but it is still only an opinion. A fourth way of validating the model, is to look at other studies that conducted similar simulation studies and compare the model outcomes with each other. A big advantage of this method is that the kind of studies that are required for comparison are relatively easy to come by. Additionally, the contents of published papers are peer reviewed so that the conclusions are generally more widely supported than an individual opinion. A downside of this method is that the modeller in the end has to determine whether the model is valid or not.

The final decision was made to validate the simulation model in this research by comparing the model outcomes to earlier simulation studies. This did not contain a large quantitative validation, but only consisted of face validation. The studies used for this validation were those that were part of the literature review in section 3.4. The model outcomes did not have to be exactly the same for our model to be valid, but general patterns and directions had to be. After all, the simulations conducted in these other studies were not the exact same. Differences in outcomes should be explainable however.

3

Literature review

The aim of this chapter is to provide a scientific background to the presented problem. Section 3.1 presents the available research basis of highway work zones. It looks at how they are designed and how traffic safety and traffic flow is presented in literature in relation to work zones. Section 3.2 looks at how infrastructure for automated driving is presented in literature. Firstly, the main classifications of automated driving and infrastructure are presented and linked to each other. Secondly the relation between automated driving and infrastructure is presented and extrapolated towards work zone design. In section 3.3 the research regarding the impact of automated driving on the traffic performance in work zones is presented. The main focus here is, again, on traffic safety and traffic flow. Section 3.4 discusses the available body of simulation research that focuses on automated vehicles in work zones. Section 3.5 synthesizes the sections that came before into a causal diagram and discusses the main findings that can be observed in this diagram. Finally, in section 3.6 the main conclusions are drawn and research gaps are presented.

3.1. Highway work zones

This section focuses on the available body of literature regarding highway work zones in the Netherlands. First, the general definitions and design principles are introduced. Recent developments regarding these design principles are also given. After laying this foundation, the available research focusing on traffic safety and traffic flow in highway work zones is analysed. The section concludes with the main takeaways that are of interest for this study.

Definitions and design principles

A work zone can be defined as a segment of road in which maintenance or construction work takes place, that affects one or more traffic lanes, or affects the operational characteristics of traffic flow through the segment (ADTSEA, 2013, Weng and Meng, 2013). The nature of these areas can vary from a traffic accident, to planned maintenance of the road surface, to large infrastructure improvement projects that require several phases of traffic management situations (Reinders, 2017). Although specific regulations regarding work zones vary from country to country they generally align. According to Reinders (2017) work zones can be categorised into three main types. These types are: static, dynamic and semi-dynamic work zones. In the Netherlands, most work zones are static work zones that provide a fixed working space for a certain amount of time. In the Netherlands, the regulations which the work zones have to comply with are described by the CROW guidelines (CROW, 2014, 2017). These guidelines describe the rules and regulations that have to be kept in mind when designing a work zone. They are based on Dutch traffic regulations, individual contracts and occupational health and safety legislation. A typical work zone design is presented in figure 3.1.

The latest research project aimed at improving the way in which Dutch work zones are designed originates from 2007. The project, executed by SWOV, looks at past accidents to explain their cause related to work zones. Based on these causes the project aims to make alterations to the work zone design to improve traffic safety. The project consists of three phases, starting of with a literature study (van Gent, 2007). This literature study is then followed up by an accident analysis (Janssen and Weijermars, 2009). Interesting results from this analysis show that the majority of the analysed accidents could have been prevented by altering the driving behaviour. For 50% of all analysed accidents, changing the driving behaviour at a tactical level (e.g. overtaking, turning, giving priority) could have reduced the probability of an accident happening. 11% of the accidents could have been prevented by changing the behaviour at the operational level (e.g. vehicle control, course, speed) and 24% could have been prevented by a change at the strategic level (e.g. route choice, mode choice). In the remaining 15% of the accidents the driver was under the influence. The final phase of the SWOV project consists of assessments of the work zones (Weijermars, 2009). Relevant results show that there are six contributors that increase the likelihood of driver mistakes. These are: (1) confusing or unclear markings and/or signs, (2) too many signs in close succession, (3) insufficient warning for lane or road blocks, (4) dangerous entrances/exits for work traffic, (5) incorrect speed limit and (6) dangerous on- and off-ramps. The resulting recommendations for improving the work zones are mainly focused on enforcement of the current guidelines.

Figure 3.1 presents a typical work zone design, including the main terminology, as described by CROW (2017). The Working Area is formed by all surface that is subtracted from traffic. It is separated from traffic by the barrier and the longitudinal barrier. All space that is left for traffic to operate in is referred to as the Traffic Area. Within the Working Area is the Buffer Space. In this space, no road workers or materials can be present, except for working traffic driving to and from the Work Space. Its main function is to separate the road workers from traffic, even in case of an accident. The Work Space is the space within the Working Area in which road workers execute their activities and where materials and tools can be placed. The start of the working space (in driving direction) is referred to as the Origin. This point is used as a starting point to determine where certain warnings and communication devices should be placed. The area that comes before the Working Area is the Transition Area. This is the area that is of most interest in this study since it is expected that most new issues will occur within this area. It starts at the first traffic sign regarding the work zone and ends at the first barrier. This area has three main functions. These are: (1) to inform, (2) to warn and (3) to communicate legal prohibitions and commandments (CROW, 2017). The Transition Area provides the road user with information regarding the roadworks and adjustments to the traffic situation. The road user should adapt its driving behaviour and position on the road accordingly. The Transition Area should be arranged in such a manner that the road user is given the opportunity to process the information and make these alterations. A correct layout is dependent on factors such as the road cross section, maximum speed, horizontal and vertical alignment, viewing distance and the presence of discontinuities (CROW, 2017). In U.S. Federal guidelines the Transition Area is split up into the advanced warning area and the transition area, where the advanced warning area is the area where communication takes place and the transition area is the area where action is required by the road user (Federal Highway Administration, 2009). In this research the Dutch terminology is used.

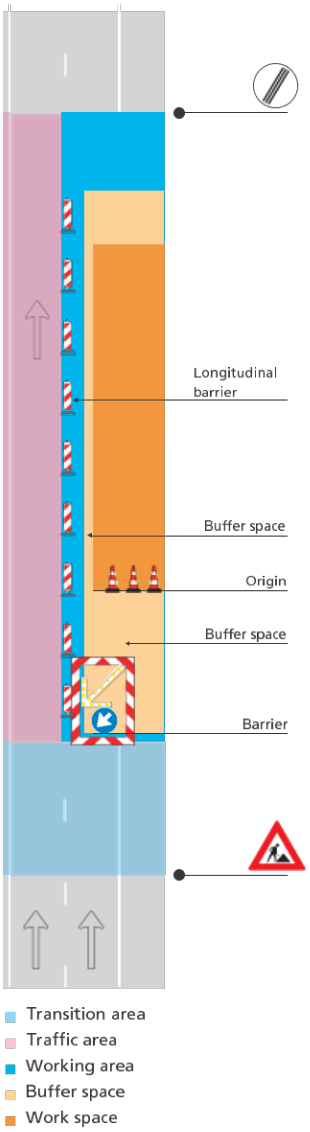


Figure 3.1: Typical work zone overview

Traffic safety in work zones

In 1999, Rumar (1999) released a report that has defined traffic safety research. In the research, ten golden rules are presented on which future EU road safety work should focus. Two of these ten golden rules have especially defined traffic safety research from that point on. The first rule is that road injuries and fatalities should be treated as a public health problem, and not as a complication of mobility. This stance allows the more extensive use of health statistics to diagnose the road safety situation. The second rule is that road safety research should focus on three main dimensions in order to produce countermeasures. These three dimensions are: traffic exposure, crash rate and crash severity. They are represented graphically in figure 3.2. When searching for ways to improve traffic safety, the goal should always be to reduce one of these three dimensions. The size of the box represents the number of people that are injured, impaired or killed, depending on the context in which safety is assessed. Mathematically, this number of people (I) can be calculated by multiplying the exposure (E) by the crash rate (A/E) and by the crash severity (I/A) (Rumar, 1999):

$$I = E * A/E * I/A$$

The crash rate is given by the number of crashes per unit of exposure. When assessing the literature focusing on the impact of work zones on the crash rate, there is no clear-cut answer. Large variation in results between studies are found due to external effects. In early research, conducted by Rouphail et al. (1988) a crash rate increase of 88% was found during the existence of a work zone, compared to the before period. A similar study, conducted by Freeman et al. (2004) in 2004 found that the presence of a road work zone resulted in no significant influence on the crash rate (0.101 versus 0.098 crashes per 1 million vehicle kilometers). SWOV (2010) and the EU funded ARROWS project (ARROWS, 1998) state that work zones can be identified as dangerous. Especially ARROWS (1998) found many studies confirming the increased crash rate in work zones. Another approach taken to explain crash rate in work zones is modeling by linear regression. Ozturk et al. (2014) constructed a linear regression model to predict the crash rate and compared this to the normal situation. Results show that the crash rate increases by 24.4% in work zones compared to the normal situation. Although determining the exact impact still remains difficult, the general consensus is that the crash rate increases significantly as a result of work zones.

The crash severity is given by the number of people injured, impaired or killed per occurring accident. All studies used in this research regarding crash severity based their results on analysing past accident data. The general stance on the impact of work zones on crash severity is inconsistent as well. ARROWS (1998) conclude that no significant difference in severity can be determined. Freeman et al. (2004) find that the number of casualties, and therefore the crash severity, is reduced with the presence of road works. The effect is very little however. Ozturk et al. (2014) finds in its literature study that the literature is inconsistent as well. Multiple studies find that crashes that happen in work zones tend to be less severe due to factors such as the lower driving speeds and the safety measures taken (Ha and Nemeth, 1995, Rouphail et al., 1988, Wang et al., 1996). Other studies claim the exact opposite however (Garber and Zhao, 2002, Pigman and Agent, 1990). van Gent (2007) concludes that no clear indication can be given on the impact of roadworks on the crash severity, but that the majority of research indicates that the injuries suffered in accidents in work zones are generally less severe.

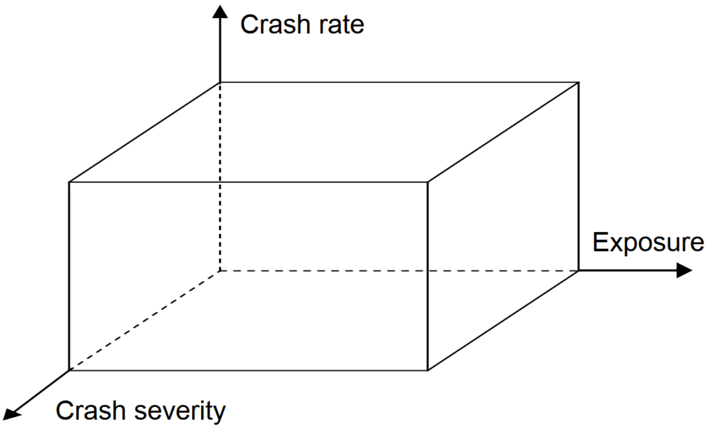


Figure 3.2: Schematic representation of the traffic safety issue (Rumar, 1999)

Exposure is the unit used to express how many times road users are exposed to an event. In the context of traffic safety it can have different units, depending on the context (van Gent, 2007). It can for instance be measured in vehicle kilometers, traffic conflicts or vehicle hours. Research specifically focusing on risk exposure are very scarce. Most research aim at reducing the crash rate or the crash severity and include exposure as a predictor. SWOV (2010) and van Gent (2007) do find that exposure data should be tracked more carefully. Both in European and American research it is found that well structured data is unavailable for the most part and that most research is done based on crash reports constructed by police officials (ARROWS, 1998, Wang et al., 1996). This makes it hard to find statistically significant relation in traffic safety due to the rareness of actual accidents. Laureshyn et al. (2010) represents this phenomenon graphically as they adopt the theories by Hydén (1987) and Svensson (1998) as represented in figure 3.3.

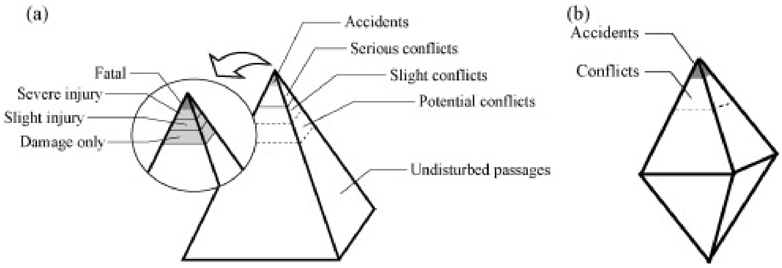


Figure 3.3: The relation between severity and frequency of elementary events in traffic (Laureshyn et al., 2010)

To overcome these limitations of the methods used in the literature presented so far, research has been done to find alternative predictors, beside actual crash data, to estimate traffic safety. Examples of these predictors are Time-to-Collision (TTC), Post-Encroachment Time (PET), Deceleration Rate (DR), Time Gap and Speed (Laureshyn et al., 2010). Additionally, these alternative predictors have been implemented in simulation environments to allow researchers to assess traffic safety in a controlled environment. Gettman and Head (2003) finds that using these predictors in a simulation environment to assess the safety of the traffic system yields viable results. TTC, PET and DR can be used to estimate the severity of the traffic conflict where Maximum Speed and Speed Differential can be used to estimate the severity of the potential collision. Gettman et al. (2008) further developed a Surrogate Safety Assessment Model (SSAM) to derive these factors from simulations and further underlined the advantages of such an approach. Especially the possibility to assess the safety of a system before implementing it is of great added value. Zhu and Saccomanno (2004) implemented this method to assess different work zone configurations. More recently Fan et al. (2013) used SSAM in combination with PVT VISSIM simulations and compared the simulation data with observed data. The results showed consistency between the observed and simulated conflicts. The applicability of SSAM in combination with automated vehicles, and specific literature on work zone simulation of automated vehicles in mixed traffic will be further treated in section 3.4.

Traffic efficiency in work zones

Most research regarding the improvement of work zones is focused on improving the traffic safety. Studies focusing on improving the work zones to improve traffic efficiency are a lot less well represented in literature. The effects that roadwork zones have on the traffic efficiency can for the most part be derived from traffic flow theory. As the CROW (2017) guidelines describe, often the speed limit is reduced from the Transition area to the end of the work zone. Additionally, the amount of lanes available in the Traffic area is often reduced and some lanes are made to be more narrow than normal, as can be seen in figure 3.1.

There are many factors affecting the exact impact of a work zone on the capacity. Weng and Meng (2012) finds a non-exhaustive set of sixteen factors that affect the work zone capacity. These factors are represented graphically in figure 3.4. They can be divided into work zone configurations, roadway conditions, work activity characteristics, environmental conditions and other factors. Zheng et al. (2010)

formulated a similar list of 18 variables that influence the capacity. Different factors that were found are: the presence of signal control and traffic signs, work zone transition length, sight deprivation, road curve radius and a month factor. For a situation with automated driving systems other factors might be of importance as well.

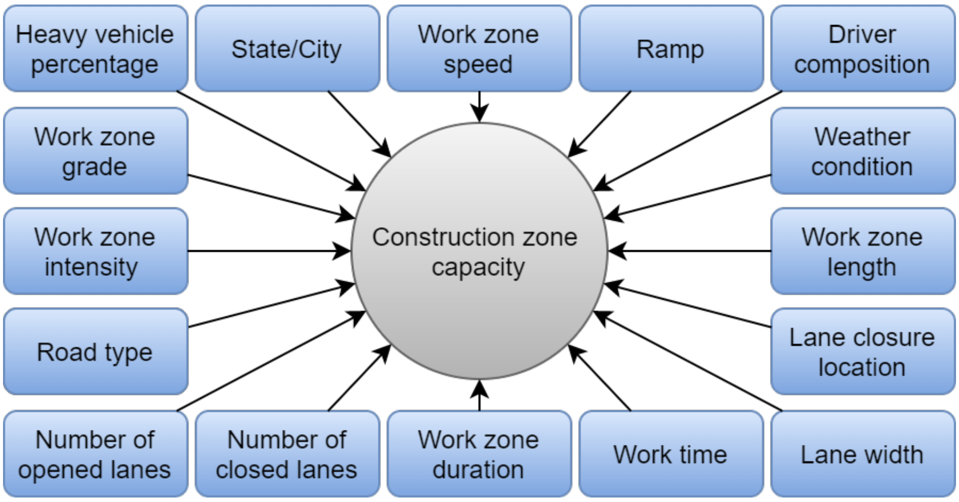


Figure 3.4: Sixteen factors affecting work zone capacity (Weng and Meng, 2012)

Because every work zone has different characteristics, the impact the zone will have on capacity will be different as well. Work zone capacity can be determined through many different ways. Weng and Meng (2013) determined that, in literature, there are three main approaches taken to estimate the work zone capacity. These are: (1) parametric approaches, (2) non-parametric approaches and (3) simulation approaches. The study defines these approaches as follows.

The parametric approach is an approach in which the capacity is determined by a set of predictors (Weng and Meng, 2013). The coefficients of these predictors can be determined by collecting data from field sites. Examples of such an approach are a multiple regression approach or a multiplicative approach. Al-Kaisy and Hall (2003) took such an approach to develop the multiplicative model to estimate the work zone capacity given below:

$$c = C_b * f_{HV} * f_d * f_w * f_s * f_r * f_l * f_i$$

In this formulation c = the work zone capacity, C_b = the base capacity, and the f_x factors represent (left to right) adjustment factors for heavy vehicles, driver population, work activity, side of lane closure, rain, lighting conditions and interactive effects. The downside of such an approach is the low estimation accuracy and the large data requirements that are needed. Advantages are that it is easy to use and requires little computational resources (Weng and Meng, 2013).

The non-parametric approach is a more complex, and generally more accurate way to estimate the work zone capacity than the parametric approach. The model used to estimate the capacity generally increases in size as the data set available is more detailed. Examples of these approaches are an elaborate decision tree approach (Weng and Meng, 2011) or a fuzzy logic approach (Zheng et al., 2011). These models are much more elaborate. Therefore no specific example is presented. This approach reaches a higher level of estimation accuracy and requires low computational resources. It does however require a large amount of data and is quite complex to use (Weng and Meng, 2013).

The big advantage of the simulation approach, compared to the other two approaches, is that simulation is not a data driven approach. The other two approaches require large amounts of data to set up the models and if data is lacking, this will have a large impact on the reliability of the outcomes. Additionally, simulation allows the researcher to inspect the exact impacts of certain factors on the capacity through experimentation. To observe driving behaviour, caused by the work zone layout, various microscopic simulation studies have been executed (Arguea, 2006, Chatterjee et al., 2009, van der Tuin et al., 2020b). The downside of this type of approach is that it is complex to use and requires a lot of computation. It does however require a lot less data to function and yields a high estimation accuracy (Weng and Meng, 2013). Specific literature on work zone simulation of automated vehicles in mixed traffic will be further treated in section 3.4.

Conclusions

This section explained what is currently known about the effects of highway work zones on traffic. First the basic design principles and the latest studies that aim at improving these design principles were presented. These studies already showed that work zones cause an increased crash risk and that the cause of crashes often lies with the behaviour of the driver. Additionally, six contributors to risk were determined.

The literature on traffic safety in work zones confirmed what was found regarding the crash risk. The vast majority of the studies found that crash risk increases in the presence of work zones. Literature of crash severity showed that the effects of work zones were less evident. Some studies showed that the severity increases where others find that it decreases. Because actual accidents do not happen very often, which makes it hard to draw clear conclusions based on crash data, additional literature was presented using Surrogate Safety Assessment Method as a predictor for exposure. Examples of predictors used in this method are Speed, Time Gap and Deceleration Rate. This method has been proven to be effective for crash prediction based on empirical data, but will be further treated with respect to automated vehicles and simulation later in this chapter.

The effects of work zones on traffic efficiency were found to be quite evident. As a result of the reduced speeds, number of available lanes and width of some lanes the traffic efficiency in work zones is lower than normal. Literature showed that there are many additional factors that influence the traffic capacity of a work zone. Sixteen of these are presented in figure 3.4. Estimating the traffic efficiency is done in three main ways. These ways are (1) parametric approaches, (2) non-parametric approaches and (3) simulation approaches. Of these approaches, the first two are data driven and the last is not. The simulation approach shows great potential for this study because it allows to construct a hypothetical situation, allows for experimentation and is able to produce its own data. This is needed since a traffic situation with automated vehicles is not available in practice.

3.2. Highway work zones and automated driving

The following section explains the research done in the field of automated driving in combination with highway work zones. In the first subsection the main classifications in this field of research are presented. These classifications are divided into classifications for automated driving, automated infrastructure and operational design domains. After this, the most recent research into automated driving in work zones are discussed.

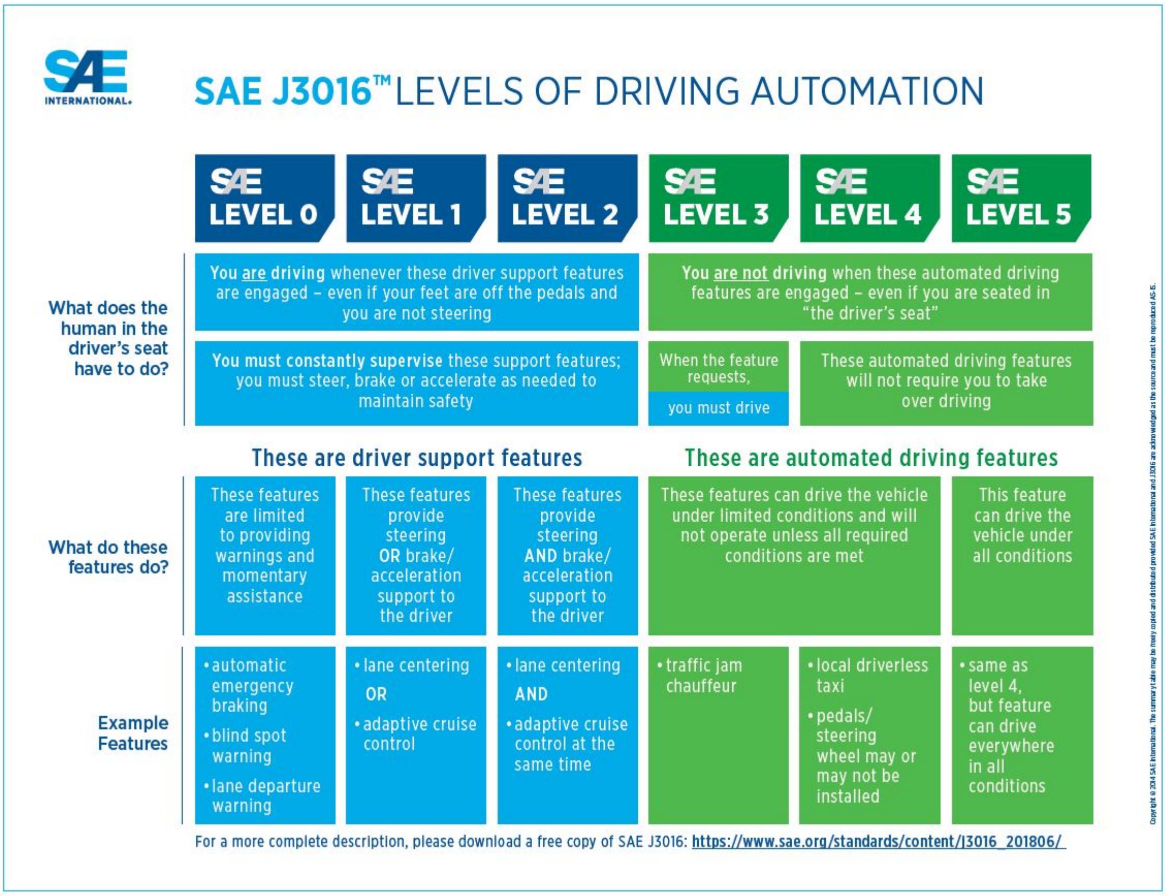
Classifications

As autonomous driving research has progressed, classifications have been made for the levels of automation in vehicles. In the same manner, a categorisation has been made to indicate the level of automation in the infrastructure. Finally a set of specific operating conditions in which both these systems are able to function has been formulated. These three aspects of autonomous driving research are presented in the following sections.

Automated driving levels

When classifying different categories of automated driving, different institutions have come to different formulations. The German Federal Highway institute has made a distinction between different levels of automation based on the expectations to the driver (Gasser et al., 2013). The Society for Automotive Engineers (SAE International, 2018) has made a categorisation based on the features that are present within the vehicle, and what activities the driver has to manually execute accordingly. The general categories that are formulated are very similar when comparing these two formulations. Gasser et al. (2013) formulates five driving levels ranging from ”Driver Only” to ”Full Automation”. SAE International

(2018) distinguishes six levels of automation but uses the same range only named differently. This formulation is presented in figure 3.5. The big difference between the two formulations is that the formulation of Gasser et al. (2013) merges SAE level 2 and 3 together where these are classified separately in the SAE formulation.



SAE J3016™ LEVELS OF DRIVING AUTOMATION

	SAE LEVEL 0	SAE LEVEL 1	SAE LEVEL 2	SAE LEVEL 3	SAE LEVEL 4	SAE LEVEL 5
What does the human in the driver's seat have to do?	**You are driving** whenever these driver support features are engaged – even if your feet are off the pedals and you are not steering			**You are not driving** when these automated driving features are engaged – even if you are seated in "the driver's seat"		
	You must constantly supervise these support features; you must steer, brake or accelerate as needed to maintain safety			When the feature requests, you must drive	These automated driving features will not require you to take over driving	
	These are driver support features			These are automated driving features		
What do these features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/ acceleration support to the driver	These features provide steering **AND** brake/ acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met		This feature can drive the vehicle under all conditions
Example Features	• automatic emergency braking • blind spot warning • lane departure warning	• lane centering **OR** • adaptive cruise control	• lane centering **AND** • adaptive cruise control at the same time	• traffic jam chauffeur	• local driverless taxi • pedals/ steering wheel may or may not be installed	• same as level 4, but feature can drive everywhere in all conditions

For a more complete description, please download a free copy of SAE J3016: https://www.sae.org/standards/content/J3016_201806/

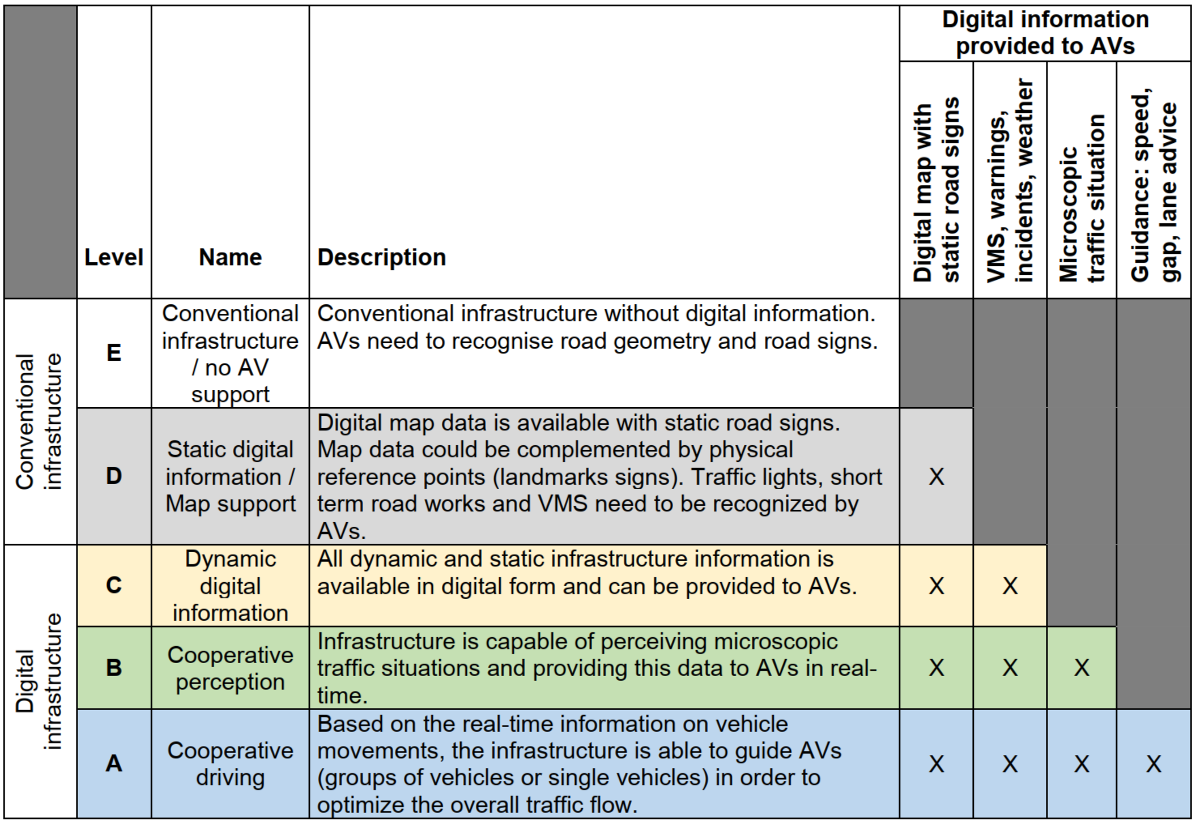
Figure 3.5: SAE J3016 Levels of Automated Driving (SAE International, 2018)

The SAE J3016 standard is the industry's most-cited reference for automated vehicle capabilities (Ulrich et al., 2020). Therefore this formulation is used as a base in this research when discussing the level of automation. The explanation of the automation levels are presented in figure 3.5, and will be briefly discussed. In a vehicle with level 0 to level 2 automation the driver is *always* in charge of the Dynamic Driving Task (DDT). In a vehicle with level 3 to level 5 automation this DDT is transferred to the Automated Driving System (ADS). Level 0 automation only includes very limited support features that increase driving convenience and increase safety by warnings and momentary assistance. Automation level 1 and 2 take over certain functions from the driver. Level 1 automation takes over either steering functions or acceleration functions. Level 2 automation takes over both these functions, but the driver is still responsible for recognizing dangerous situation which the vehicle can not handle. Level 2 automated vehicles are put into practical commercial use on a larger scale within the coming years (Inagaki and Sheridan, 2019). Level 3 automated vehicles go one step further in terms of automation in the sense that the vehicle is able to drive freely under a limited set of conditions, and is able to recognize dangerous situations or situations where not all conditions for automated driving are met. When this occurs the vehicle prompts the driver to take over control again. The driver must be able to take over control when the ADS requires it. Level 4 automated vehicles are able to drive fully autonomously under a specific set of conditions, but does not require the driver to take over control. This is the first level of automation that does not require intervention of a driver under any circumstances. Finally, level 5 automated vehicles are the same as level 4 automated vehicles in terms of driving capabilities, but these can function under all conditions. These can be considered as fully automated vehicles.

Some valid critique can also be found in literature on this formulation. Inagaki and Sheridan (2019) find that an automation level that requires a take over by the driver, such as is the case in level 3 automation, can lead to dangerous situations. These kinds of systems are already in place on a smaller scale in aviation, where pilots are trained extensively to react to these take over requests. Despite the training, these take over request have still led to numerous accidents or issues that can be traced back to a lack in situational awareness. Implementing such systems in cars, where users are relatively untrained, does not seem plausible then. Adding the notion to the level 3 formulation stating that the driver might not be good at taking over control is deemed necessary. A second point of critique was found by Ulrich et al. (2020). They state that while the SAE formulation does provide a common language for automation functionality, it still lacks the information under which circumstances the different levels of automation function. To close this gap, the concept of Operational Design Domains has emerged in literature. These ODDs will be explained later this chapter. Despite this critique this formulation is still common language in automation research and so it will be used as such in this study.

Infrastructure Support levels for Automated Driving (ISAD)

Similar to the classifications that were made for vehicle automation, recently too classifications were made to indicate the level of infrastructure automation. This was done in a study by Carreras et al. (2018) as part of the larger EU-funded INFRAMIX project. This research project focuses specifically on the transition period in which automated vehicles (at different levels) will become more and more common, and what this will require from the road operators. In their research a simple classification scheme is formed that can be used to assign levels to parts of the road network in order to give automated vehicles guidance on the readiness of the network for automated vehicles. This ISAD classification scheme is presented in figure 3.6.



	Level	Name	Description	Digital information provided to AVs			
				Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Conventional infrastructure	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs.				
	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.	X			
Digital infrastructure	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time.	X	X	X	
	A	Cooperative driving	Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

Figure 3.6: Levels of the Infrastructure Support for Automated Driving (Carreras et al., 2018)

The infrastructure is divided into five classes which are in turn separated into the conventional- and digital infrastructure. As the infrastructure automation level increases, more digital elements are added to the conventional infrastructure. Support level E provides no additional information to the automated vehicle apart from what the sensors of the vehicles observe themselves. Support level D provides the vehicle with a static digital map of the network section. An example of this is a navigation system that knows speed limits in certain areas. Support level C and higher implements dynamic digital information. This includes periodically updated information on incidents, work zones, variable message signs etc. Support level B allows for the perception and communication of the microscopic traffic situation by infrastructure sensors. This does not directly mean that vehicles will be able to reach a form of cooperative perception, because this requires a certain level of automation from the vehicle side as well. This could be a future possibility. These infrastructure support levels only say something about the infrastructure. Support level A goes one final step further by using the real-time information, collected by infrastructure sensors, to guide the automated vehicles to optimize traffic flow. It does so by giving advice on driving speeds, routes, lane usage, headways etc.

These support levels are only meant to be used to describe road sections. This is in line with common practice of infrastructure deployment (Carreras et al., 2018). These levels are connected with a certain level of connectivity with the automated vehicles. Level E requires no connectivity. Level D requires only sporadic connectivity to update the digital map present within the vehicle. At level C, where the information provided is also dynamic, a more frequent connection in needed. Once every few seconds the information collected by the infrastructure should be sent to the vehicle. At level B and A a real-time connection would be required since the vehicles can then be updated at a very high frequency. The effects of these support levels, as well as the possibilities that come with higher levels of automation remain a large gap in this formulation. Seeing that the formulation is rather new, there is a lot to be studied regarding these effects in the context of support levels.

Operational Design Domain (ODD)

The Operational Design Domain (ODD) is the description of the operating conditions in which the automated driving system is designed to properly operate (Ulrich et al., 2020). This description includes factors related to both the physical and the digital infrastructure (Harah, 2016). Physical infrastructure includes infrastructure such as roads, shoulders and traffic signs while the digital infrastructure involves traffic management-, communication- and GPS systems. Then there are also factors such as traffic law and regulation, the weather or time-of-day that define the ODD. It is a very broad concept.

Several different studies have aimed at constructing a (non-exhaustive) set of ODD factors that form the whole field of driving automation. Koopman and Fratrik (2019) have constructed a list of factors that can be used as a basis for further research to validate the functioning of autonomous vehicles. These are very high level however and are formulated to encompass the entirety of automation research. For this research the factors that are of most interest are those related directly to infrastructure. To this end Aigner et al. (2019) constructed a more specific set of factors that are of interest when determining whether an automation system is able to function. Ulrich et al. (2020) extended this list based on literature study and expert workshops as a part of the EU-funded MANTRA research initiative. This list is presented in table 3.1.

Most of the ODD attributes are related to infrastructure, with a separation between physical and digital infrastructure. The separation between static and dynamic infrastructure is a little less straightforward. Attributes such as the road are clearly static. One could argue however that communication between the infrastructure and traffic is dynamic. Despite the fact that the information communicated might be dynamic, Ulrich et al. (2020) categorized this ODD attribute as static because the infrastructure needed for communication is static.

Table 3.1 merely shows the attributes. The specific requirements for these attributes differ between SAE automation level. SAE level 5 automated vehicles are able to drive in all ODDs. This means that these vehicles require no specific ODD attributes. Lower levels of automated vehicles will have specific attribute requirements however. These specific requirements are not clearly defined in literature yet. Additionally, the effects that individual attributes can have on the functioning of automated vehicles are undefined in literature. This is a gap in the literature that should be covered by new research.

Table 3.1: Infrastructure related attributes Ulrich et al. (2020)

ODD attribute	Physical / Digital infrastructure	Static / Dynamic
Road	Physical	Static
Speed range	Physical	Static
Shoulder or kerb	Physical	Static
Road markings	Physical	Static
Traffic signs	Physical	Static
Road furniture	Physical	Static
Traffic	-	Dynamic
Time	-	Dynamic
Weather condition	-	Dynamic
HD map	Digital	Static
Satellite positioning	Digital	Static
Communication	Digital	Static
Information system	Digital	Static
Traffic management	Digital	Dynamic
Infrastructure maintenance	Physical/Digital	Dynamic
Fleet supervision	Digital	Dynamic
Digital twin of road network	Digital	Dynamic

Automated driving in work zones

Now that a clear image is obtained of the context and terminologies of infrastructure for automated driving, the latest research in this field can be discussed. The role that infrastructure plays in the implementation of automated vehicles was long underrepresented in scientific research (Lytrivis et al., 2018a). Early studies conducted by Al-ayat and Hall (1994) and Jacob Tsao (1995) looked at how the concept of the smart systems can be implemented and what challenges may arise on the way. These studies do not look at what specific systems should be implemented, but look at the problems of implementation from a governance oriented viewpoint. Only in the last decade Zhang (2013) identified studies that look at intelligent vehicle/highway systems as a concept that combine both physical and digital infrastructural aspects. Scientific studies regarding digital infrastructure for automated vehicles are much more prevalent than those regarding the physical infrastructure that might aid the functioning of automated vehicles.

Recently a multitude of (inter)national research initiatives emerged, studying the impact on vehicle automation of the infrastructure, funded by the European Union. Examples of these initiatives are DRAGON (Vermaat et al., 2017), MAVEN (Lu and Blokpoel, 2017, Rondinone et al., 2018, Schindler et al., 2019), Traficom (Kulmala et al., 2019), INFRAMIX (Berrazouane et al., 2019, Carreras et al., 2018, Erhart et al., 2019, Lytrivis et al., 2018a,b, Markantonakis et al., 2019) and MANTRA (Aigner et al., 2019, Penttinen et al., 2019, Ulrich et al., 2020, van der Tuin et al., 2020a,b). Naturally these research initiatives vary in characteristics. They differ from each other in terms of research scope, time horizon and focus. MAVEN, for instance, aims to contribute to solutions for automated vehicles in an urban environment. This is a different focus from the other projects that are more focused on highway scenarios. DRAGON, Traficom, INFRAMIX and MANTRA study how national road authorities (NRAs) can make full use of the potential of vehicle automation. The last three of these look especially close at what the role of the infrastructure is in this context.

DRAGON focuses on how to support the movement towards high and full highway automation (Vermaat et al., 2017). This research presents three main findings, linked to infrastructure, that can be relevant for this research. Firstly, the study emphasizes that any infrastructural changes that will contribute to the functioning of autonomous vehicles, also should help conventional vehicles. This is because there will be a long transition period in which there will be both conventional traffic and many different levels of autonomous vehicles present. The second main finding of this research is the identification of the potential of segregating autonomous vehicles from conventional vehicles. This could speed up the implementation of autonomous vehicles although it could also lead to capacity reduction and high investments. The third main finding interesting for this research is the identification of the potential of communication between vehicles and the infrastructure. Through this communication the autonomous vehicles could receive information on advisory speed or routes to maximize the capacity. These findings are only based on theories and literature, and are not based on any quantitative experiments. Quantification of the effects these findings might have is advised for future research.

As seen earlier in this chapter Traficom and MANTRA have added to this research field by elaborating upon the ODD factors that are relevant for automated vehicles. Kulmala et al. (2019), the main report in the Traficom project, presents a list of attributes of ODDs for highly automated vehicles. Ulrich et al. (2020), as part of the MANTRA project, elaborates upon this list by adding four new attributes that are important for the on-site ODD. The outcome of these two lists is presented in table 3.1. These attributes are then further split into sub-attributes. Ulrich et al. (2020) finishes by giving example requirements for each ODD sub-attribute. The description of all relevant ODD sub-attributes is presented in Appendix B. Again, no clear solutions are given for all ODD attributes. These ODD attributes are only formulated for SAE level 4 and higher automated vehicles with a time horizon of the year 2040. This means that the transition period in which many different and lower automation levels will be present in combination with conventional vehicles remains uninvestigated. Additionally, no estimations are given about the possible effects that certain ODD factors might have.

The research initiative that does study the transition period in which automated and conventional vehicles coexist, with specific attention to infrastructure, is INFRAMIX. The main target of the project is to adapt the physical and digital infrastructure to ensure uninterrupted, predictable, safe and efficient traffic (Lytrivis et al., 2018a). In this study three high-risk traffic scenarios are identified. These are (1) dynamic lane assignment, (2) roadwork zones and (3) bottlenecks. Lytrivis et al. (2018b) further elaborates on these high-risk scenarios by formulating several use cases with automated vehicles per scenario.

The roadwork zone scenario, which is of interest for this study, was selected because it generally does not match well with the ODD requirements that were formulated for CAVs (Lytrivis et al., 2018a). Therefore it is expected that CAVs will experience difficulties in these environments. Gerdes and Zwijnenberg (2018) also identified these risks. Requirements for the quality and consistency of road signs and -markings are one example of the difficulties that might arise in these situations. Conventional road users are able to handle inconsistencies in roadwork zones fairly well. Automated vehicles function very poorly in these situations. Consistency in the roadwork design will therefore become key in the future (Gerdes and Zwijnenberg, 2018). The study also identifies opportunities for smart infrastructure to aid the CAVs in these roadwork zones. The opportunities lie with the ODD factors related to communication, information systems, traffic management and other digital infrastructural elements from table 3.1. The exact capabilities of automated vehicles in roadwork zones are still uncertain. This require further research by conducting field tests or driving simulator experiments. This is still difficult to study because automated vehicles are still a very small fraction of the vehicle fleet in practice (Berrazouane et al., 2019).

In order to study these specific effects better, first more global research focusing on the general vehicles interactions and their effects is needed. To this end, INFRAMIX aims to simulate the high-risk traffic scenarios trough microscopic traffic simulation in order to observe what interactions automated vehicles will have with one another and with conventional vehicles in these difficult situations (Berrazouane et al., 2019, Erhart et al., 2019). Studies that already conducted such simulation studies will be discussed in section 3.4.

3.3. Automated driving and traffic performance

This section discusses the main general findings in literature regarding the traffic performance of automated driving. The traffic performance is separated into traffic efficiency and traffic safety. Traffic efficiency is briefly discussed, since most of the research regarding this topic uses simulation as a method. These specific studies are discussed in section 3.4. Traffic safety is discussed more extensively. Main challenges identified in literature are presented and limitations of the scientific studies conducted so far are mentioned.

Traffic efficiency

Traffic efficiency is a general term that can be explained as the extent to which a certain transportation input can meet the travel demand of people in a transportation system (Gaitanidou and Bekiaris, 2012). Translated to the context of automated driving, the definition of traffic efficiency is the extent to which the road network can process the amount of vehicles, given the penetration rate of automated vehicles and their settings. Often used key performance indicators (KPIs) used in research to measure traffic efficiency are road capacity, travel time, speed (variability) and headway (Penttinen et al., 2019).

In general, the main consensus is that when all vehicles on the road would be automated, the traffic efficiency there would be optimal (Calvert et al., 2017, Liu and Fan, 2020, Mehr and Horowitz, 2020, Penttinen et al., 2019). This is due to several assumptions regarding the driving behaviour of CAVs, such as a smaller headway, more constant driving speed and a quicker reaction time. It is also found however that the efficiency will initially worsen with the introduction of automated vehicles (Le Vine et al., 2015). This is due to the conservative settings that automated vehicles will most likely contain in the introduction phase, as well as the unfamiliarity that conventional drivers will have with the automated vehicles.

Where initial studies were focused on the general effects of CAVs on traffic efficiency, lately more studies are conducted that aim at quantifying these effects. Calvert et al. (2017) identified the main gaps in the scientific knowledge regarding the effects of automated driving, including the effects on traffic efficiency. The three most important methods that are used to study these effects are identified. These methods are field operational tests, empirical analysis and driving simulation methods.

Empirical analysis refers to analyzing the situation that is already in place on current roads. The main difficulty of this method is that there are currently far too few vehicles present with automated driving systems to gather enough data. Field operational tests are considered to be the next best thing to empirical analysis. These tests are performed in controlled situations in real life environments. The main downsides of these types of tests are that they are expensive to carry out, and that they still yield only a limited amount of data. Because of the controlled nature of the tests this data can also be unrealistic. Of the three methods, the simulation method allows for the most flexibility without major investment. Simulations are cheap to carry out, and they allow for iterative changes to the test environment. Human behaviour is more difficult to test in these environments and it is highly relying on the model input. Because CAVs are not deployed on a large scale in practice yet, nearly all current studies regarding the quantification of traffic efficiency use some form of traffic simulation (Penttinen et al., 2019). Some studies use driving simulators to observe interactions between human drivers and CAVs, or to observe the effects of take over requests on the traffic efficiency. Other studies use microscopic simulation since the individual interactions between vehicles are of interest in such studies. The specific methods used in these types of studies will be discussed in section 3.4.

Traffic safety

Connected and Automated Vehicles have been identified in literature as a major opportunity to increase traffic safety. The extend to which this new technology contributes to safety varies a lot in literature however. Chan (2017) and Shladover (2009) found that many public agencies make claims that automated vehicles could reduce traffic fatalities by more than 90%. This is based on the knowledge that more than 90% of traffic accidents can be traced back to human error. Although these statements are eye-catching for the public, they are neither accurate nor responsible for a public agency to make. This statement is only based on one factor, while in reality the situation is much more complex.

Sivak and Schoettle (2015) come to three conclusions that should be kept in mind when conducting traffic safety research regarding automated vehicles. Firstly, they state that the expectation of zero fatalities with automated vehicles is not realistic. New risks might occur that will most certainly create traffic fatalities. Secondly, it is found that the expectation that an automated vehicles will drive more safely than an experience, middle-aged driver is not a forgone conclusion. As sensors and the driving software improve, the decision making of an automated vehicle will improve. But simply assuming that the vehicles are able to make complex decisions can be dangerous. Finally it is also found that during the transition period when conventional and automated vehicles coexist and share the road, traffic safety might actually worsen for at least the conventional vehicles. This can be due to vehicle interactions or because of errors in the automated vehicles. When keeping these three findings in mind, many safety conclusions coming from studies conducted until now should be reconsidered.

An approach using more different measure is proposed by Smith et al. (2015). They propose using net number of traffic violations, extreme maneuvers, take over requests, exposure to near-crash situations and response to near crash situations as a measure for the safety impacts of automated vehicles. The main issue with measuring these instances, is the low current penetration rate of vehicles with automated driving systems in the vehicle fleet. This means that there is very little data to collect in practice which makes it difficult to make proper estimations based on practical data. To this end many studies use simulations to gather more data. These types of studies will be discussed in section 3.4.

In addition to these well known safety factors, Litman (2020) made a list of new risks that have been identified in literature in relation to automated driving. These new risks include:

- Hardware and software failures. The systems present in the automated vehicles can fail, although it is difficult to predict the frequency of these errors occurring.
- Malicious hacking. Any connected vehicle is prone to hacking or other malicious activities by third parties.
- Increased risk-taking. Because of the increased feeling of safety, users might tend to take higher risks. Litman (2020) calls this phenomenon offsetting behaviour or risk compensation.
- Platooning risks. Platooning has many potential benefits such as reduced emissions and less congestion. Having human drivers interact with these platoons might cause new risks however.
- Increased total vehicle travel. Because automated driving will likely increase convenience and comfort for travelers, their behaviour will change accordingly. This can increase the total vehicle travel which increases risk exposure.
- Additional risks to non-auto travelers. This only applies in urban areas. There the sensors might experience difficulties with perceiving pedestrians and cyclists.
- Reduced investment in conventional safety strategies. In an effort to stimulate use of automated vehicles, the safety measures for conventional traffic can become of lesser interest for regulators.

These risks are difficult to study and are therefore mostly treated in theoretical studies. Further research into these factors can only be conducted once more global effects, such as the effect on traffic flow and the direct safety effects, become better documented.

3.4. Work zone simulation of mixed traffic

The research specifically focusing on work zone simulation of mixed traffic with CAVs and CV is very limited. van der Tuin et al. (2020b) analysed the effects of CAVs at different penetration rates in two dynamic work zones (winter maintenance and a safety trailer). The microscopic simulations were executed using PTV VISSIM 11. Traffic efficiency was assessed by looking at the absolute travel time over the stretch of road and the safety was assessed using SSAM, as defined by Gettman et al. (2008). The simulations varied the penetration rate of CAVs between 0% and 100%, used different CV driving logic and used different communication policies for the CAVs. CAV driving logic was not varied. Three communication strategies were applied. In the first strategy, a signal tells the CAVs that a work zone is ahead and that the CAVs have to switch to the available lane directly 500m ahead of the work zone. In the second strategy the CAVs are told the same, but they are also told to adopt a longer headway (5 seconds) to increase the possibilities for other vehicles of switching lanes too. In the third strategy, no additional information is sent to CAVs. They then should switch lane automatically once they notice the speed differences between lanes. Also different flow/capacity ratios and speed limits were applied. These flow/capacity ratios were always designed to create a free flowing traffic situation at 0% CAV penetration rate (max 0.56).

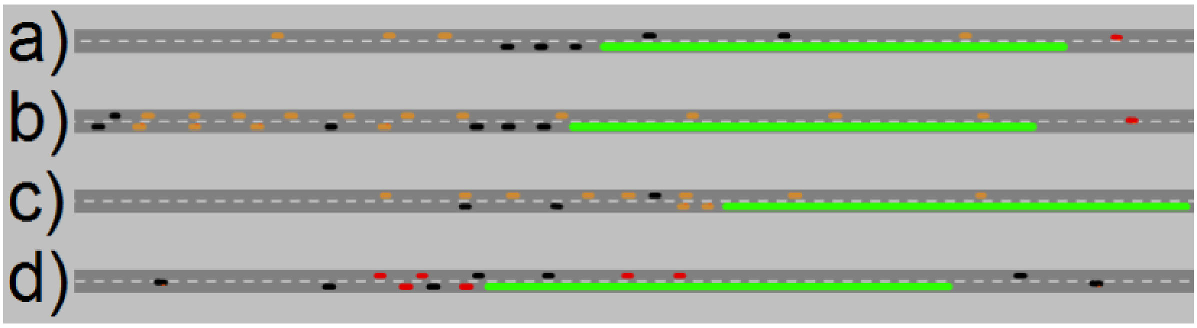


Figure 3.7: Example simulations of the safety truck (van der Tuin et al., 2020b)

Figure 3.7 shows four screenshots of simulations executed by van der Tuin et al. (2020b). CVs are represented in black. CAVs that have received a message to use specific driving rules are represented in orange and CAVs driving according to their own behaviour are red. Situation A has only a F/C-ration of 0.37. The other situations use a 0.56 F/C-ratio. In both situation A and B the CAVs are told to adopt a 5 seconds headway. This leads to reduced capacity, especially visible in situation B due to the congestion right before the work zone. After passing the work zone all vehicles behave normally again. In situation C CAVs are made aware of the presence of the safety trailer but are told to maintain their regular headway. This does not lead to decrease in capacity as much as in situation A and B but does make most CAVs move to the left lane early which leads to vehicles blocking each other near the safety trailer. In situation D no additional communication for CAVs is put in place. Similar to situation C, vehicles have to wait for a gap near the safety trailer, but vehicles spread quite evenly.

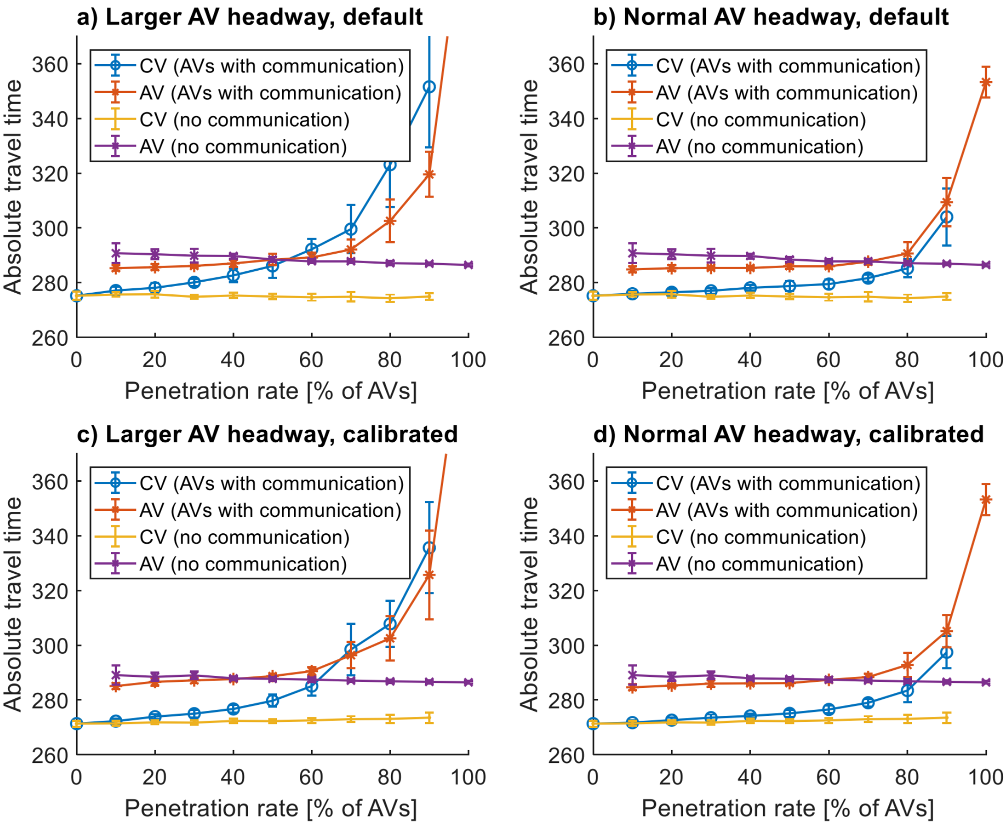


Figure 3.8: Travel time results of a safety trailer work zone (van der Tuin et al., 2020b)

Further results in this study showed that the communication strategy that did not communicate anything to the CAVs at all was most effective. This led to the fewest merging problems and allowed traffic to flow best. Communicating the presence of the work zone to CAVs generally lead to the CAVs shifting to the left lane very early which lead to merging issues near the work zone. The phenomenon is presented figure 3.8 by the fact that the travel times exponentially increase with the penetration rate because all CAVs want to merge early. CAVs generally have a higher travel time, independent of the communication strategy, due to the fact that they comply to the speed limit better than CVs. Similar results as presented in figure 3.7 and 3.8 were found for the winter maintenance vehicle. Difference in results were found, but this was largely due to the moving speed of the dynamic work zone.

The safety analysis in this study was limited to two SSAM factors. Post Encroachment Time(PET) and Time To Collision(TTC) were used with threshold values of 5 seconds and 1.5 seconds respectively. Because of the low F/C-ratio no conflicts were identified in the simulations. Additionally, the CAV driving behaviour and the nature of VISSIM simulations make it difficult to make safety estimations. As a result of this, little could be concluded on the safety impacts. van der Tuin et al. (2020b) state that SSAM has not been verified for CAVs and that it is unsure if this model makes sense for CAVs. Furthermore, no additional risks are included in the SSAM, such as software failure and loss of control. No sensitivity analysis of the PET and TTC thresholds was executed. For future studies it is recommended to use safety factors such as formulated by Smith et al. (2015) to assess the safety. Other factors that are often seen in literature to assess safety are speed variability, headway, the number of lane changes.

Other studies that did not look at work zones specifically, but looked at highway scenarios with general discontinuities (e.g. on-ramps, off-ramps and weaving sections) are much more numerous. Aria (2016) used microscopic simulation to construct such a scenario to compare 0% and 100% CAVs scenarios. It was found that the average speed during the peak hour increased by 8.48% on the modelled segment and that the dispersion around the mean speed was smaller for the 100% CAV scenario. This is in line with what one would expect. Rios-Torres and Malikopoulos (2017) conducted a similar study. They found that the baseline scenario (0% CAVs) yielded a slightly higher traffic flow than the 100% CAVs scenario due to a small portion of the road users neglecting the speed limit. When the F/C-ratio increased the 100% CAVs scenario showed a vastly superior traffic flow however. These findings are presented graphically in figure 3.9. Both these studies did not look at safety aspects.

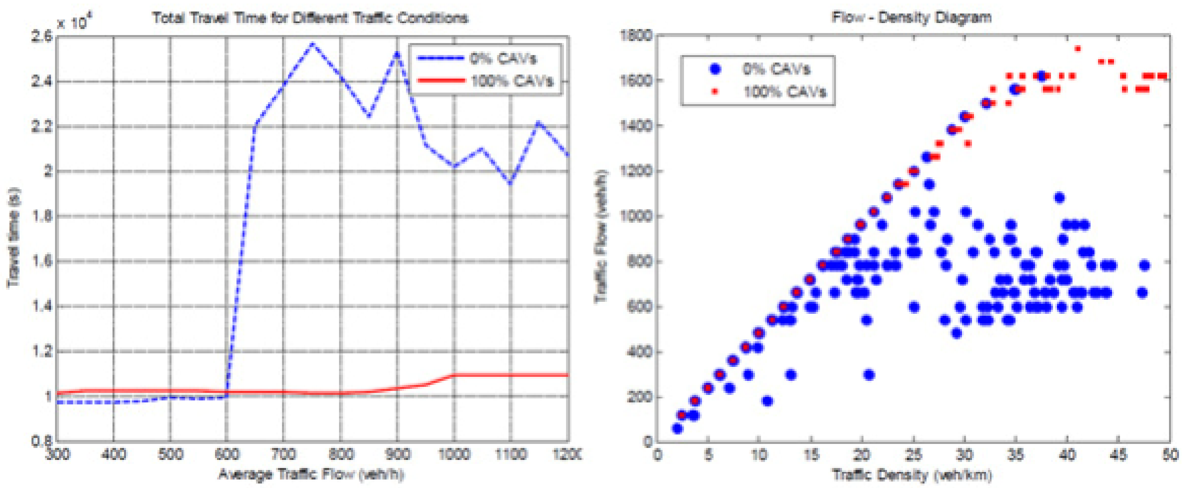


Figure 3.9: Time-flow and flow-density graphs for a 0% and 100% CAV penetration rate (Rios-Torres and Malikopoulos, 2017)

Studies that used microscopic simulation to assess the safety aspects of CAVs were conducted by Morando et al. (2017, 2018) and Papadoulis et al. (2019). Morando et al. (2017, 2018) compared two extreme scenarios (0% vs 100% penetration rate) and found that the safety increased significantly with the higher level of automation. Papadoulis et al. (2019) varied the penetration rate between 0% and 100% with steps of 25%. It was concluded that the safety levels improved as the penetration rates increased. Even at lower penetration rates the difference was significant. All these results are limited by the methods that are used, as the authors state themselves. One limitation is that of the car following model (Wiedemann 99) that is present in PTV VISSIM that simulates human driving behaviour. van der Tuin et al. (2020b) proposed a way to alter this car following model to better represent CAVs to improve the simulations. Another limitation is that the measures in SSAM are based on human behaviour. How well these measures hold up with CAVs is questionable. This is why the conclusions of Morando et al. (2017, 2018) and Papadoulis et al. (2019) cannot be directly extrapolated to other areas. Their methods are valid due to the fact that large populations of CAVs are not yet present in practice however. These methods can be improved based on research such as van der Tuin et al. (2020b).

3.5. Causal diagram

Figure 3.10 presents the causal diagram that was constructed based on the preceding sections. This causal diagram is made to help formulate the simulations and help identify research gaps. The dotted square represents the traffic system. This is the general system of traffic driving on the road. The gray factors on the left represent external factors. In a way, these factors set the rules of the system. The black oval factors are the system factors. These are the factors that are within the system itself. On the right side the system output is presented in blue. In traffic, many interrelations exist that form traffic safety and efficiency as seen in the literature. Therefore these factors were aggregated into these two main pillars. Finally the orange factors on top present the future developments with relation to automated driving. These can also be seen as external factors, but since they are new features that will develop in the future, they are kept separately.

By no means does the causal diagram include all possible factors that form and influence the entire traffic system. As stated in section 3.1, many factors have been identified. These also include factors such as weather conditions, road marking quality, time of day, type of road and many more. External effects regarding weather, and the quality of road markings and traffic signs are left out of scope because these factors can not be studied with simulation methods. Many of the relations in the causal diagram have already been discussed earlier in this chapter. Now the most noteworthy features that can be identified are discussed.

Feedback loops

The first two important sets of relations are the relations between headway, speed, road capacity, F/C-ratio and congestion. In these relations, two feedback loops can be identified. The first feedback loop is made up of speed, road capacity, F/C-ratio and congestion. This positive feedback loop shows that as congestion forms, the speed drops which reduces capacity even more which in turn increases congestion more. Note that the term ”positive” here means that the effect is increased with time, not that the relation is ”good”. The second feedback loop here is a negative feedback loop. This means that the effect corrects itself constantly, not that it is ”bad”. This negative feedback loop is made up of headway, road capacity, F/C-ratio, congestion and speed. This loop shows that as congestion forms, the headways are reduced, which increases road capacity, which relieves congestion slightly. This second feedback loop therefore relieves the effects of the first one. Note that the external factor of traffic demand is very important here to neutralize the congestion.

Uncertain relations

The three orange factors all three have relations that are presented in black. This is because these relations are still uncertain. The effect that the level of automation of CAVs will have on their own headway and speed is well known. The headway can be hard programmed, and the speed will be very constant. The effect this will have on the average headway and speed of all traffic is uncertain however. How will conventional drivers respond to the settings of the CAVs? Because this is uncertain, the automation level of CAVs has a uncertain impact on the headway and the speed variability. This same principle holds for the CAV penetration rate. The only certainty here is that as the CAV penetration rate increases, that the average speed decreases. This is because CAVs will not drive over the speed limit, where drivers do. This reduces the average speed in traffic. The effect of the penetration rate on the headway is uncertain. At a 100% penetration rate the headway can be predicted very well, but here again the effects of the CAVs on conventional drivers in uncertain. That is why the effect of CAV penetration rate on headway is uncertain. This is the same for speed variability. At a 100% penetration rate the speed variability is very little. At lower penetration rates the effect is uncertain however.

The effect that the presence of traffic control/sign will have on the traffic system is highly dependent on the type of control or sign. Zheng et al. (2010) stated that this variable increases traffic efficiency and safety. This is quite logical, since that is most often the goal of signs and signals in traffic. The way in which traffic safety and efficiency are influenced however is uncertain because this is dependent on the type of control. In figure 3.10 this factor is shown to influence speed and speed variability, but it could influence many more of the factors in the system such as headway or lane changes. To keep the diagram readable, not all possible influences were included.

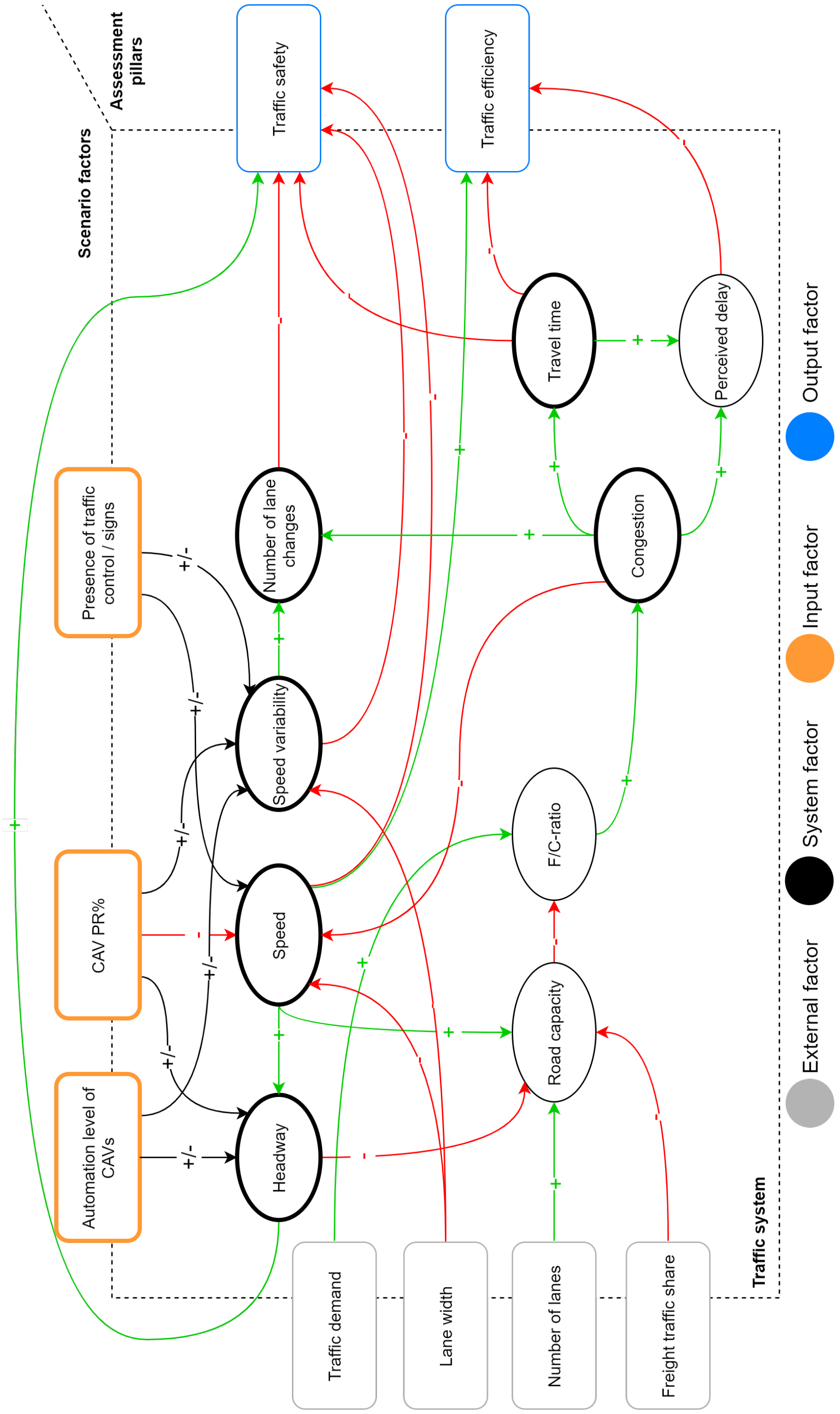


Figure 3.10: Causal diagram

3.6. Conclusions and research gaps

There are many studies that focus on factors that are of importance for traffic efficiency and traffic safety. Interrelations between these different factors are quite well known as well. This makes that there are very few knowledge gaps regarding the traffic system. The effects that a new disruptive innovation such as connected and automated vehicles will have on the traffic system is still highly uncertain however. The concept of connected and automated vehicles is relatively new. The amount of available research focusing on the impacts these vehicles will have is therefore limited. The impact that the level of automation will have, as well as the impact of the penetration rate is uncertain. Most research focuses on high levels of automation at a high penetration rate. The uncertainties lie within the area of lower penetration rates and lower automation levels however. What interactions between CAVs and conventional traffic will occur? How does this influence safety factors? How does this influence the traffic efficiency?

A clear scientific basis should be built that studies effect of CAVs on traffic efficiency and safety. Studies exist that make a first attempt at traffic simulation with lower penetration rates. Especially high risk situations such as weaving sections and work zones are identified to be of importance, since most difficulties are expected here. Further simulation research of work zones is recommended to include the implementation of different communication strategies. van der Tuin et al. (2020b) makes a start with this and makes recommendations for further research to analyse the impact of CAV behaviour more in-depth, and to look at communication strategies that might improve the functioning of traffic with connected and automated vehicles. Wen (2018) adds to that the recommendation to test these strategies in different work zone types.

In conclusion, the impact of different levels of vehicle automation at varying penetration rates on the traffic system should be studied more in depth. This can best be done in high risk situations, since here these effects become most visible and most difficulties are expected here. Work zones are such a high risk scenario. Additionally it is uncertain what road operators can do to improve both traffic efficiency and safety. By researching these three factors(automation level, penetration rate, communication strategy) in a work zone environment an estimate can be made of the possible impacts, and insight can be gained on how to influence traffic in the future in the best way.

4

Simulation design

Now that a better understanding is gained of the traffic system in the context of automated driving, the factors that are of interest are translated into simulations. The factors that were found to be most important in figure 3.10 are translated into the building blocks of VISSIM as formulated in figure 4.1. These building block were formulated by Barceló (2010). They are explained in this chapter. Section 4.1 presents the network set-up, which focuses on the building block of infrastructure. Section 4.2 presents the driving logic, which focuses on the building block of traffic. Section 5.3 presents the simulated scenarios, which in part presents the building block of control although the communication strategies themselves are presented later in chapter 5. Section 4.4 presents the Key Performance Indicators(KPIs) that are the final building block of the model output.

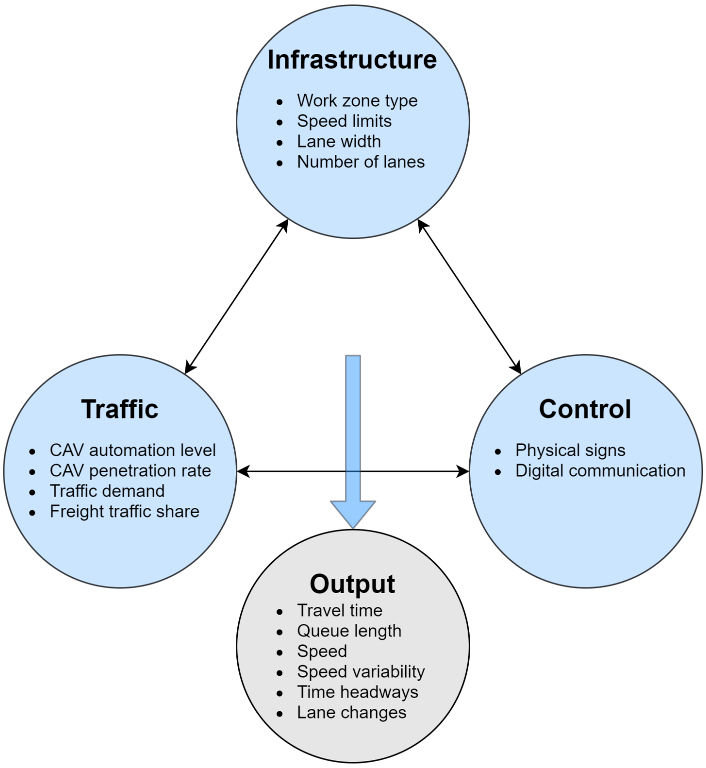


Figure 4.1: Model building blocks (adapted from Barceló (2010))

4.1. Network set-up

For the microscopic simulations tests that were executed in this study two networks were selected. These networks both contained a simplistic representation of a typical roadwork zone configuration. The selection of work zone configurations was based on literature and input gathered in a workshop that was held with the VolkerWessels traffic management team at VolkerWessels Infra Competence Centre. The documentation of this workshop can be found in Appendix C. For simplicity reasons no real life network was chosen for the simulation. The two work zones that were selected are a right lane closure, and a 3-1 contraflow system. This section describes these two work zones, and explains how these work zones were simulated within the VISSIM simulation software. The first subsection focuses on the right lane closure and the second subsection focuses on the 3-1 contraflow system.

Right lane closure

The general lay-out of a right lane closure, as prescribed by CROW (2020), is presented in figure 4.2. This figure represents the chosen network of a right lane closure. The different colors in the figure are explained in section 3.1. The network contains one straight road, with the work zone in the middle of the network. The vehicles that enter the network start with a road section that is 2.5km long and contains two lanes with a speed limit of 100 km/h, as is the legal highway speed limit in the Netherlands. After 2km, and 500m before the work zone, the speed limit is reduced to 90 km/h, and the first indication of the road works are communicated to the vehicles in the network. This leaves the vehicles 500m of space to react to the work zone and to switch to the left lane to continue driving. At the start of the work zone, where the road only consists of one lane, the speed limit is further reduced to 70 km/h. This section with one lane is 5.5km long. This section was chosen to be this long to be sure that the traffic normalizes again to observe interaction effects between CAVs and conventional vehicles while they are driving on one lane. After the 5.5km of work zone, the road transitions to a normal state again with two lanes and a 100 km/h speed limit. Here both lanes are used again by traffic and the vehicles leave the network at the end of the road section. This final normal road section is 1.5km long.

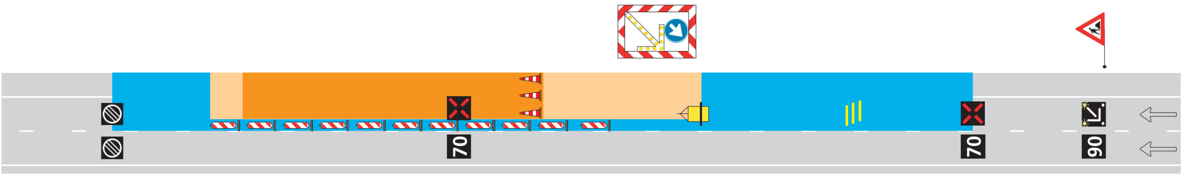
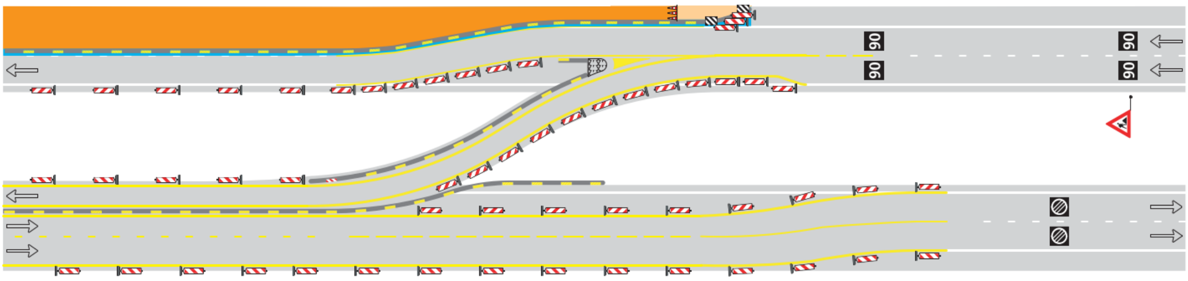


Figure 4.2: Right lane closure (CROW, 2020)

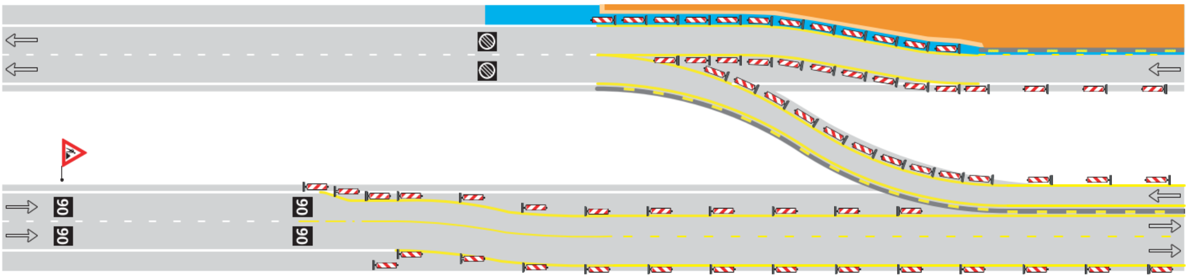
The network contains some important features that were interesting to this study. Firstly, the network contains two speed reductions. Interesting to observe was how different types of vehicles (CAVs and conventional vehicles) adhered to these speed reductions and to what kind of interactions this led. Conventional vehicles were expected to adjust their speed more gradually than CAVs which could lead to unsafe situations. Secondly, the network contains a bottleneck. This is the section where the road transitions from two lanes to one lane. Although the vehicles are made aware of this transition 500 meters before the actual bottleneck, it was still interesting to see how they coped with surrounding traffic and to what interactions this led. The final interesting feature was the road section containing only one lane. In this section the vehicles are forced to follow one another. This section was especially interesting with lower penetration rates of CAVs. The interactions that both types of vehicles had with one another while following became very clear then.

3-1 contraflow system

Figure 4.3 presents the general lay-out of a 3-1 contraflow system. Based on this figure and the description as given by the CROW (2017) guidelines the second simulation network was given shape. In contrast to the simulated network of the right lane closure, this road work system was simulated in both driving directions. This is because, as is visualized by the yellow road markings in figure 4.3, the lane width is reduced in both driving directions.



(a) Start of 3-1 system: Vehicles from the right are distributed over both driving directions



(b) End of 3-1 system: Vehicles from the right are redirected back to their own driving direction

Figure 4.3: 3-1 contraflow system (CROW, 2020)

The vehicles enter the network through a two-lane road with a speed limit of 100 km/h. This road is, similar to the right lane closure, 2.5km long. After 1.5km, and 1km before the 3-1 contraflow system itself begins, the speed limit is reduced to 90 km/h. This applies to both driving directions. The communication of the speed reduction at 1km ahead of the 3-1 system is based on the CROW (2017) guidelines. As can be seen in figure 4.3a, the lanes in the driving direction that have to be split up are reduced in width. Both lanes are reduced from a 3.50m width to a 2.75m width. The vehicles in this direction are forced to follow each other until the end of the work zone. When the work zone ends, the two lanes that were split up come together again as can be seen in figure 4.3b. The initial speed limit of 100 km/h is reinstalled, and the vehicles drive in a normal situation until they leave the network. The opposing driving direction is very similar in terms of speed limits. Here too the vehicles are allowed to drive 100 km/h outside, and 90 km/h inside the work zone. Within the work zone the lane width is also reduced. The reduction is different from the other driving direction however. Here the lane width is reduced from two lanes at 3.50m to one lane of 3.25m and one lane of 2.75m. This again is in line with the guidelines. The lanes in this direction are not separated from one another. Subsequently vehicles are allowed to switch lanes as they see fit.

This network contained some interesting features as well. The first interesting feature was the speed reduction. The simulated behaviour that vehicles showed was expected to be similar to the behaviour shown with a right lane closure. However it was still interesting to observe this. The second feature that was of interest is the separated lanes. This was interesting in two ways. First it is important to note how vehicles dealt with the separation itself. How will they choose what lane to take? Secondly, here too it is interesting to observe how vehicles interact with each other within the separated lanes. Overtaking is not possible here so they had to adjust their speeds. Secondary interaction effects were expected to occur in which conventional vehicles having to adjust their speeds to the speeds of the CAVs. The third and final feature that was interesting about this network is the lane width reduction. We know that in practice a lane reduction has effect on the driving behaviour of human drivers as well as automated driving systems. It was uncertain how well this behavioural change can be observed in simulation. It was interesting to see nonetheless.

4.2. Vehicle driving logic

As mentioned before, the simulations in this study generally contain two types of vehicles. These types are the conventional human operated vehicles and the connected and automated vehicles (CAVs). The conventional vehicles are the same for all scenarios. For the CAVs however, three different types of driving logic are applied in the simulations. This section describes the way in which these different types of driving logic are formulated, and how they take shape in simulation. First the formulation of conventional vehicles is presented. This section is a bit more elaborate, because a basic description of the way in which VISSIM formulates driving behaviour is provided as well. After this the formulation of the CAVs is given. For all types of vehicles the features that are expected to be most important are discussed.

Conventional vehicles

The term conventional vehicles is used for vehicles that are fully operated by human drivers. It is assumed that these vehicles are not equipped with any auxiliary systems such as (adaptive) cruise control or automated emergency braking. This assumption still holds for a large part of the current vehicle fleet, although these types of systems become more and more standard in new cars. Even though these conventional vehicles have existed for many years, modelling them requires alterations to the default VISSIM driving behaviour. The driving behaviour in VISSIM consists of four main subjects that are changed to formulate the driving behaviour in this study. These four subjects are Following, Car following model, Lane Change and Lateral. The most important subject, the car following model, the lane changing behaviour, and the settings that are changed to create the desired behaviour are discussed.

All vehicles in VISSIM use a car following model derived from Wiedemann (1991). This model is called the Wiedemann 99 car-following model. It sets the perception boundaries of vehicles and sets the rules that these boundaries form. The Wiedemann 99 model includes ten factors such as following distance, lane change behaviour and acceleration and deceleration behaviour.

Although VISSIM itself already has default values for various different vehicles types, it is still advised to always use Wiedemann 99 parameters that are calibrated for the traffic situation that is simulated (PTV Group, 2019). The default car following parameters in VISSIM are representative of a free flowing traffic situation with little crowdedness. In order to see the effects of different CAV driving logic and different penetration rates, the work zones need to be simulated with a crowded traffic situation. Different parameters, calibrated for crowded traffic, are therefore required. van Beinum et al. (2018) conducted a study that was aimed at calibrating the Wiedemann 99 parameters for this traffic situation. Although this study looked more specifically at weaving and merging behaviour, and not at behaviour in work zones, it is expected that the behaviour matches the work zone behaviour. This is expected because model conditions such as the crowdedness and the merging activities that come with the work zones are similar to the conditions in the study by van van Beinum et al. (2018).

Table 4.1 shows some of the default parameters that form the total driving behaviour of cars. In this table only those parameters are included that are changed according to the findings by van Beinum et al. (2018). These adjusted parameters are included in the table as well. The parameters starting with 'CC' are the ten parameters that together form the base of the Wiedemann 99 car-following model. The other parameters are additional parameters that are not included in this traditional model, but that do add to the driving behaviour.

The first two parameters specify the number of objects a vehicle can perceive while driving. The calibrated conventional vehicle is able to perceive information of 8 different objects. This is much more than the VISSIM default value. Objects include all possible features that can be implemented in a VISSIM network such as traffic signs and traffic lights, but also other vehicles on the road. This is also why the number of interaction vehicles is set to 99. This simply means that the number of interaction vehicles is limited by the number of interaction objects. The third and fourth parameter indicates the area in which each vehicle receives information. This area extends from 250 meters ahead of the vehicle to 26 meters behind the vehicle. The relatively short look back distance can be explained by the fact that drivers tend to pay less attention to what is behind them in crowded traffic situations and look more to what is ahead. The fifth parameter indicates whether the absolute braking distance in enforced or not. The absolute braking distance is the distance that it takes for the vehicle to come to a complete stop. If this distance is enforced, the vehicle never drives closer to its preceding vehicle than this distance. In reality, human drivers drive closer to their preceding vehicle quite often, especially in

Table 4.1: Driving behaviour of conventional vehicles: default and calibrated van der Tuin et al. (2020b)

Parameter	**Vissim default**	**Calibrated**
Number of interaction objects	2	8
Number of interaction vehicles	99	99
Look ahead distance (min – max, m)	0-250	0-250
Look back distance (min – max, m)	0-150	0-26.16
Enforce absolute braking distance	No	No
Use implicit stochastic	Yes	Yes
Cooperative lane change	No	No
CC0 – Standstill distance (m)	1.5	2.33
CC1 – Headway time (s)	0.9	0.5
CC2 – Following variation (m)	4	3.91
CC3 – Threshold for entering ’following’ (s)	-8	-9.87
CC4 – Negative ’following’ threshold (m/s)	-0.35	-1.21
CC5 – Positive ’following’ threshold (m/s)	0.35	1
CC6 – Speed dependency of oscillation (rad/s)	11.44	11.44
CC7 – Oscillation acceleration (m/s2)	0.25	0.24
CC8 – Standstill acceleration (m/s2)	3.50	3.50
CC9 – Acceleration with 80 km/h (m/s2)	1.50	1.50

busy traffic. The sixth parameter indicates whether the behavioural distributions, such as desired speed and acceleration, should be simulated stochastically. This stochasticity accounts for human deviations. For human drivers this option is definitely an added value. The seventh parameter indicates whether or not vehicles change lanes cooperatively. By enabling this parameter vehicles give each other space to change lanes. By disabling it, vehicles can only change lanes when there is space available and this space is not created for each other. In practice vehicles often do not give each other space to change lanes.

Now the parameters that are part of the Wiedemann 99 model will be discussed. CC0 is the standstill distance. This is the distance two vehicles keep when they are both standing still in traffic. As seen in table 4.1, calibration found that vehicles on average tend to keep 2.33 meter distance. CC1 is the headway time. This is the minimal following distance, in seconds, that vehicles keep on average. VISSIM calculates the preferred following distance for each vehicle individually based on this value. CC2 is the following variation. This is the unintentional variation that a driver allows when following the preceding vehicle. CC3 is the threshold for entering following. This defines the beginning of the deceleration process. At this distance, in seconds, the driver recognizes a preceding slower vehicle. CC4 and CC5 are the negative and positive following threshold. These indicate the sensitivity a following vehicle has to a speed difference with the preceding vehicle. The closer the value is to zero, the more sensitive the reaction. As can be seen, vehicles tend to react more sensitive when they have to break than when they can accelerate. This is a logical reaction. The final four parameters describe the boundaries of acceleration/deceleration. CC6 indicates the influence of the distance traveled on the speed oscillation. The network simulated in this study is too small for this parameter to have a real effect but for totality reasons it is still kept in this report. CC7 represents the minimum value at which vehicles accelerate and decelerate. CC8 represents the desired acceleration when a vehicle start from standstill. CC9 also represents the desired acceleration but then at 80 km/h.

There are quite some differences in the default driving logic embedded within VISSIM and the calibrated driving logic for conventional vehicles as formulated by van Beinum et al. (2018). The first major difference is the number of objects a driver can receive information from. This number is increased from two to eight objects. This will mainly have influence on the ability of drivers to change lanes. The second difference is the field in which drivers can perceive other objects. The look back distance is vastly reduced in the calibrated driving logic compared to the default value. This can be explained by the fact that drivers tend to pay less attention to what is behind them in crowded traffic situations and look more to what is ahead. This will also have its impact on the ability to change lanes. The main changes to the Wiedemann 99 car following parameters mean that drivers generally anticipate better, but also take more risk and react more severely to changes in traffic. The increased anticipation is represented by the increased threshold for entering following and the smaller variations in driving speed. The higher risk taking is represented by the reduced headway time, although vehicles also maintain a longer standstill distance. The increased reaction severity is represented by the negative and positive following thresholds. This means that conventional vehicles tend to accelerate and decelerate a lot more severely than the VISSIM default. In the simulation this behaviour is expected to lead to more speed variation and irregularities.

Connected and automated vehicles

As stated earlier in section 3.2, the exact driving logic of CAVs is still up for debate. This relates to the different levels of vehicle automation that are possible, but also to uncertainties regarding the exact settings CAVs will have when they become more prominent on the road. Because of these uncertainties, CAVs are simulated in this study with three different types of driving logic. The formulated behaviour, as well as the simulation parameters that form this behaviour in VISSIM are treated in this section. In this study it is assumed that the vehicle fleet only consists of passenger cars. No trucks or other heavy vehicles are included.

The three CAV driving logic types that are used in this study were first formulated in general as part of the CoEXist project by Olstam and Johansson (2018). These three types of driving logic are the (1) cautious, (2) normal and (3) all knowing driving logic. Cautious CAVs always adopt safe behaviour. The vehicle keeps quite large gaps between the preceding vehicle and it requires quite a lot of space to change lanes. This behaviour is designed based on the principle that the CAV should never be responsible for any accidents. The normal CAVs show driving behaviour similar to human drivers, but with the added capacity to measure distances and speeds with sensors. Olstam and Johansson (2018) describe this behaviour to more like a benchmark than as an actual driving behaviour. However the behaviour is included in this study for the sake of completeness. The all knowing CAVs have vastly improved perception and prediction capabilities that lead to smaller gaps for all manoeuvres and situations. Especially at higher penetration rates these vehicles are expected to show cooperative behaviour.

The exact settings that are required to simulate these types of driving logic are described by Sunkennik et al. (2018). This study was also executed as part of the CoEXist project, in collaboration with PTV Group with the goal to formulate the exact simulation parameters that form the described driving behaviour. This study gives general advice on how to change the default parameters in VISSIM to better simulate CAV driving logic, but also recommends numerical values. It does so for the car following model and the lane change behaviour. These two aspects are discussed in the sections below. Since the meaning of the individual parameter was already given in the previous section, here only the differences in behaviour are discussed.

Car following

Table 4.2 presents the following parameters of the three types of CAVs that are simulated. The first seven parameters are not explicitly part of the car following model. Here the only difference between cautious and normal CAV behaviour is the enforcement of the absolute breaking distance. This is quite a severe difference however, since it means that the cautious CAV will maintain a much longer headway than the other CAVs and the conventional vehicles. The all knowing CAVs are more advanced than the cautious and normal CAVs which is represented by a higher number of interaction objects and a longer look ahead distance. The all knowing CAV is even able to perceive more objects than the conventional driver.

The other parameters in table 4.2 are part of the car following model itself. All parameters that represent variation in speed and following distance are much lower than the variations shown for the conventional vehicles earlier this chapter. This is a result of the assumption that is made in literature, that CAVs will drive much more constant. It can also be seen that this variation is the same for all types of CAVs. This applies for the parameters CC2, CC4, CC5, CC6 and CC7. These are the same among the different types of CAV driving logic. The main differences in car following between the types can be found in headway time, the threshold for entering following and the acceleration. The more advanced the CAVs

Table 4.2: Driving behaviour of CAVs: Cautious, Normal and All knowing Sunkennik et al. (2018)

Parameter	**Cautious**	**Normal**	**All knowing**
Number of interaction objects	2	2	10
Number of interaction vehicles	1	1	8
Look ahead distance (min – max, m)	0-250	0-250	0-300
Look back distance (min – max, m)	0-150	0-150	0-150
Enforce absolute braking distance	Yes	No	No
Use implicit stochastic	No	No	No
Cooperative lane change	Yes	Yes	Yes
CC0 – Standstill distance (m)	1.5	1.5	1
CC1 – Headway time (s)	1.5	0.9	0.6
CC2 – Following variation (m)	0	0	0
CC3 – Threshold for entering ’following’ (s)	-10	-8	-6
CC4 – Negative ’following’ threshold (m/s)	-0.1	-0.1	-0.1
CC5 – Positive ’following’ threshold (m/s)	0.1	0.1	0.1
CC6 – Speed dependency of oscillation (rad/s)	0	0	0
CC7 – Oscillation acceleration (m/s2)	0.1	0.1	0.1
CC8 – Standstill acceleration (m/s2)	3	3.5	4
CC9 – Acceleration with 80 km/h (m/s2)	1.2	1.5	2

become, the closer they will drive to the preceding vehicle and the quicker they will accelerate. All knowing vehicles will also adopt a slightly shorted standstill distance compared to the other vehicles. Although this difference is only marginal, in combination with features that are explained later in this section this could lead to congestion dissolving quicker.

Lane changing behaviour

Lane changing involves numerical parameters as well as functionalities that can be specified by on/off. Both these types of parameters are explained in this section. First the numerical parameters are explained and then the other functionalities come to pass. Table 4.3 shows the numerical parameters that make up the bounds for adjusting the driving speed for a lane change. For every type of CAV, the table contains the parameters for the ’own’ vehicle and the ’trailing vehicle’. The trailing vehicle is the vehicle that drives in the new lane where the own vehicle want to merge into. Together, the parameters in the table specify a deceleration curve for both the own vehicle and the trailing vehicle (PTV Group, 2019).

Table 4.3: CAV lane changing behaviour numerical parameters Sunkennik et al. (2018)

	Cautious		**Normal**		**All knowing**	
Parameter	**Own**	**Trailing**	**Own**	**Trailing**	**Own**	**Trailing**
Max. deceleration (m/s2)	-3.5	-2.5	-4	-3	-4	-4
-1 m/s per distance (m)	80	80	100	100	100	100
Accepted deceleration (m/s2)	-1	-1	-1	-1	-1	-1.5

The maximum deceleration specifies the upper bound, or maximum amount, of braking that is allowed to change lanes. For the own vehicle this means the maximum braking to make the merge possible. The merge is only executed if the necessary amount of braking for the trailing vehicle does not exceed the maximum deceleration for the trailing vehicle. The accepted deceleration specifies the lower bound, or minimum amount, of braking that is allowed when changing lanes. This again also applies for the trailing vehicle. The -1 m/s per distance parameter represents change in deceleration as a result of the distance to the object the vehicle is braking for. It reduces the maximum deceleration with increasing distance from the emergency stop distance linearly by this value, until it reaches the accepted deceleration. To make this more clear, figure 4.4 presents the deceleration curve of the Normal CAVs for lane changing that is formed by implementing the parameters as given in table 4.3. When the deceleration equals -1 m/s2, the two line overlap.

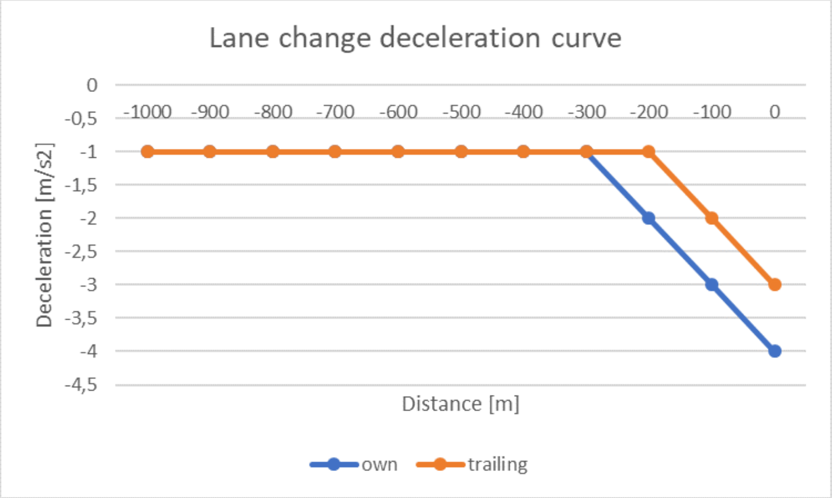


Figure 4.4: Lane change deceleration curve

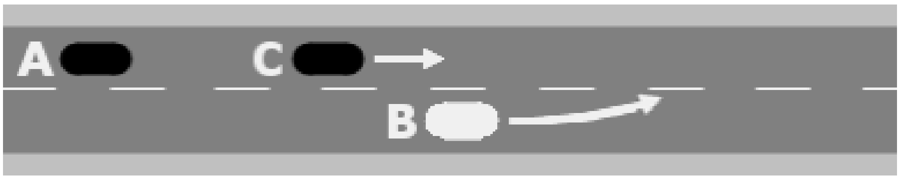
Apart from the deceleration parameters for the own and trailing vehicle, there are also lane changing features that are assumed to be implemented in CAVs that are not implemented for conventional vehicles. These features and some additional parameters are presented in table 4.4. These feature are the same for all CAVs, regardless whether they are trailing or leading.

Table 4.4: CAV lane changing features Sunkennik et al. (2018)

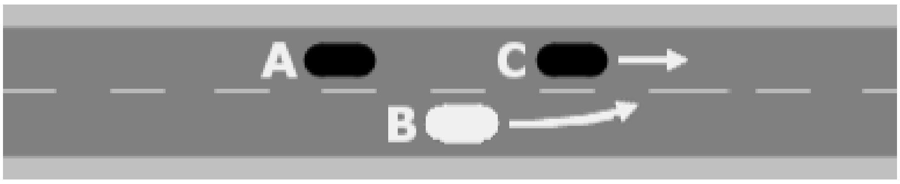
Parameter	Cautious	Normal	All knowing
Advance merging	On	On	On
Cooperative lane change	On	On	On
Safety distance reduction factor	1+EABD	0.6	0.5
Min. headway (front/rear) [m]	1	0.5	0.5
Max. deceleration for cooperative braking [m/s2]	-2.5	-3	-6

The first two features that CAVs use when changing lanes are advanced merging and cooperative lane changing. Both these features are aimed at vehicles giving each other space to change lanes when they have to and to make lane changes more fluid. To illustrate the functioning of advanced merging, figure 4.5 presents some examples. In figure 4.5a vehicle A wants to switch lanes. With advanced merging enabled, vehicle A will recognize the speeds vehicle B is driving with. If vehicle B is driving slightly slower or the same speed, vehicle A will reduce its speed slightly and move into the gap behind B. If advanced merging is disabled, vehicle A will only slow down when it approaches the emergency stop distance behind B. In figure 4.5b vehicle B wishes to change lanes. With advance merging enabled, vehicle A recognizes and uses cooperative braking so that vehicle C can slow down slightly as well. This allows vehicle B to change lanes. When advance merging is disabled, the situation as depicted in figure 4.5c occurs. Here vehicle A leaves the cooperative behaviour to its preceding vehicle. In this case that vehicle, vehicle C, is already to close so it overtakes vehicle B with the result that now vehicle A is too close to vehicle B as well. This can lead to unnecessary congestion forming. With advanced merging enabled this will not happen as often. When cooperative lane changing is enabled vehicles will give each other space to change lanes, by changing lanes themselves. This is only effective in a network with three or more lanes on a road. In this study the maximum number of lanes on a road section is two. However, to keep the CAV driving logic consistent with (Sunkennik et al., 2018) this functionality is enabled.

(a) A recognizes speed of B and acts accordingly



(b) A and C give B space to change lane with advanced merging



(c) A and C overtake B without advanced merging

Figure 4.5: Advance merging principles (PTV Group, 2019)

The safety distance reduction factor is a factor with which the regular safety distance is multiplied for vehicles that want to change lanes. This value after multiplication is the temporary safety distance a lane changing vehicle uses. After the lane change the vehicle adopts the regular safety distance again. As seen in table 4.4 the cautious driving logic always uses the regular safety distance and 'enforce absolute braking distance'. This makes it harder to change lanes. The normal and all knowing CAV driving logic reduce the regular safety distance by 40% and 50% respectively. This safety distance is limited by the minimal headway. This factor is needed, because at very low speeds the safety distance (in seconds) might take on a value that is too small. This is why the safety distance is further limited by the minimal headway. Finally the maximum deceleration for cooperative braking limits the amount of cooperative behaviour vehicles can show in situation such as in figure 4.5. As can be derived from these values, all knowing CAVs are allowed to drive much more cooperatively than cautious and normal CAVs.

Functions and distributions

Apart from the decision making parameters that form the individual types of driving logic that were described up to this point, all vehicles in PTV VISSIM also make use of functions and distributions. All functions and distributions that are present within VISSIM are based on a range of empirical studies (PTV Group, 2019). The functions and distributions that are used for CAVs are based on the research by Sunkennik et al. (2018). Functions are used to account for differences in the driving behaviour and different vehicle properties during acceleration and deceleration. These functions differ per type of vehicle. Distributions are used to formulate the desired speed of vehicles. They can also be used to model vehicle weight, power or occupancy, but these factors are out of scope for this study. There is no difference in functions between CAVs and conventional vehicles. The only difference, which is a significant one, is that the stochasticity of the functions are vastly reduced. The distributions are vastly different between CAVs and conventional vehicles, with the same goal of reducing the variation in driving behaviour for CAVs. This simulation decision is based on the assumption that CAVs show more uniform driving behaviour and was further formulated in the CoExist project in collaboration with PTV Group. For both the functions and distributions this will be illustrated by giving an example.

Figure 4.6 presents the maximum acceleration function for cars in VISSIM in blue with the upper and lower bound of this value presented in orange. Every vehicle that is generated during the simulation is appointed a maximum acceleration curve that lies within these bounds. This is one of the many stochastic elements that lies at the basis of the traffic simulation environment. This same function also applies to all three types of CAVs. However, the upper and lower bounds are not included for the CAVs. This eliminates the stochastic element for CAVs and makes the simulation more deterministic since all CAVs are appointed the same maximum acceleration function. Functions similar to this function are also implemented in VISSIm for the desired acceleration, the maximum deceleration and the desired deceleration.

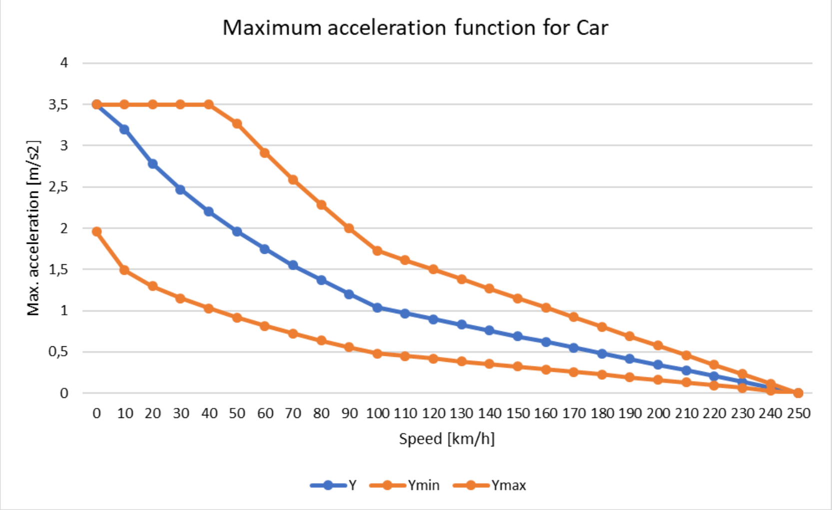


Figure 4.6: Max. acceleration function for Car

Figure 4.7 presents the desired speed probability distribution for road sections with a 100 km/h speed limit for both the conventional vehicles and the CAVs. All CAVs use one same speed distribution per speed limit. The conventional vehicles are presented in blue and the CAVs in orange. The horizontal axis represents the speed and the vertical axis presents the probability of each speed being chosen as the desired speed for each generated vehicle. When a vehicle is not hindered by other traffic, a driver will travel at his/her desired speed. Similar probability distributions as this are made for road sections that have other speed limits, although their general shape is similar to this one. As is clear in the image, conventional vehicles are very likely to drive faster than the legal speed limit. CAVs stick to the speed limit very well with a variation of only 2 km/h. This assumption again is based on earlier research that was quantified by Olstam and Johansson (2018) in collaboration with PTV Group. This assumption is expected to have a very large effect on the simulation outcomes, since it determines driving speeds directly. According to the VISSIM 11 user manual the desired speed distribution is of particular importance, as it has an impact on link capacity and achievable travel times.

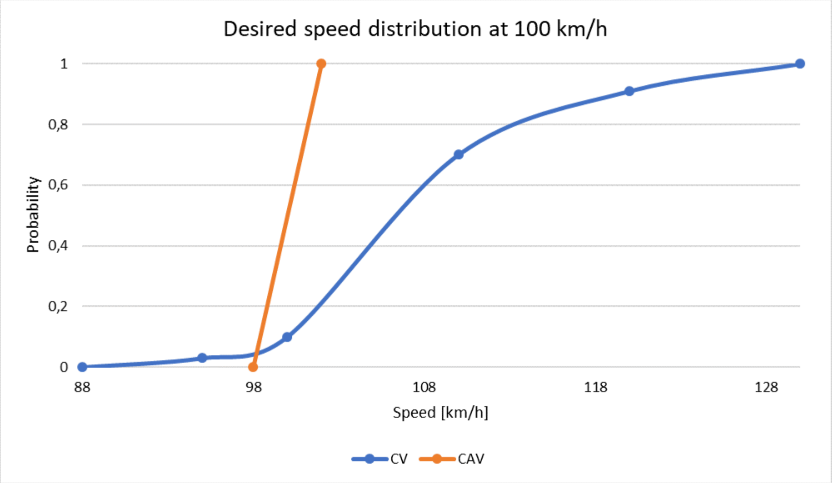


Figure 4.7: Speed distribution at 100 km/h

Calibration and validation

As mentioned at the start of this section, it is advised by PTV Group (2019) to calibrate the driving behaviour parameters or to use driving behaviour parameters that are already specifically calibrated for the scenario that is studied. Seeing that the scenario that is studies in this research is a future state model, most of the parameters can not be calibrated based on empirical data. This includes the parameters and distributions for the three types of CAVs (cautious, normal & all knowing). As mentioned these three formulations were however specifically constructed to represent the driving behaviours as described in the CoEXist project (Olstam and Johansson, 2018, Sunkennik et al., 2018). The CV driving behaviour parameters have already been calibrated by van Beinum et al. (2018) for a crowded traffic environment on a weaving section in the Netherlands. Even though the work zones do not contain weaving sections, the driving behaviour is assumed to be representative since the rest of the environment (e.g. crowded, mandatory merging because of the bottleneck) are similar. Additional calibration of these parameters is thus not done as part of this study. This is a large assumption that should be noted.

As was mentioned in chapter 2, an extensive quantitative validation is not part of this study due to the unavailability of empirical data and time constraints. The model is therefore only calibrated and not fully validated. To partly account for this, the the model outcomes are face validated by comparing them to the outcomes of earlier simulation studies. The studies used for this validation are those that are part of the literature review (section 3.4). The model outcomes do not have to be exactly the same for our model to be valid, but general patterns and directions have to be. After all, the simulations conducted in other studies are not the exact same. Differences in outcomes should be explainable however. The face validation is described as a part of the reflection in chapter 6.

4.3. Simulation scenarios

There are two base scenarios because there are two chosen networks. These base networks are the most simple scenarios, that represent a situation with no automated vehicles, that will be used as a benchmark to compare all other scenarios to. After this base scenario has been presented, the way in which the variation scenarios are designed is discussed.

Base scenarios

The base scenarios are built according to the network structure as presented in detail in section 4.1. Here only a brief description is given regarding the layout. Both scenarios start with a motorway with 2 lanes and a speed limit of 100 km/h. After 2.5km the road work zone begins where the vehicles in the network have to react to a change in road layout and speed limit. After several kilometers of road works the road returns to a normal state after which the vehicles leave the network again on the other side.

The traffic demand that is used as vehicle input in the simulations is based on Henkens et al. (2015). Their report synthesizes many different traffic capacity values for the most frequently occurring road configurations, based on empirical studies. It also includes values for highway roadwork zones. The reported capacity values are based on a set of assumptions. These assumptions are in line with the assumptions made in this report, such as the assumption that the road work is static and that there are no discontinuities (e.g. on- or off-ramps). The only major difference is that the capacities are based on 15% freight traffic, while in this study freight traffic is out of scope. This means that the capacity values have to be corrected for freight traffic.

The way in which this can be done is also described by Henkens et al. (2015). Base capacities are given in veh/h. This unit is dependent on the percentage of freight traffic. Per default, Henkens et al. (2015) assume 15% freight traffic in their capacity calculations. In order to correct for this assumption the veh/h have to be converted to pcu/h. Pcu stands for passenger car unit. This is done by correcting the capacity, given in veh/h, with the pcu-factor and the percentage of freight traffic. The pcu-factor is a factor that indicates the amount of space and capacity a freight vehicle takes up compared to a passenger car. In literature many different pcu-factors have been found to be plausible. Henkens et al. (2015) use a pcu-factor of 2.0 which means that every freight vehicle counts for two passenger vehicles.

Here this same pcu-factor is used. The formula that is used for conversion is:

$$C_{pcu} = C_{veh} * [(f_{pcu} - 1) * \%VA + 1]$$

With:

- C_{pcu} = road capacity in [pcu/h]
- C_{veh} = road capacity in [veh/h]
- f_{pcu} = the pcu factor
- $\%VA$ = the share of freight traffic in [%]

The capacities given by Henkens et al. (2015) are maximum capacities. In this research the goal is to study the effects of CAVs on the traffic efficiency and safety. To see the effects on traffic efficiency, the flow/capacity-ratio need to be quite high. Otherwise no congestion would ever form in the simulations and nothing could be concluded about traffic efficiency. In real life a F/C-ratio of 0.8 or higher can already cause significant congestion. Because of the absence of irregular human driving behaviour in simulation this F/C-ratio needs to be higher to create congestion. Therefore in this study a F/C-ratio of 1.0 is used. This means that the capacities that are found are used as input for the traffic simulations. The capacity that is given for a road with two lanes, in which the right lane is closed, is 1500 veh/h. Correcting this capacity with the formula given above yields a corrected capacity of 1725 pcu/h. This value is used as the vehicle input for the right lane closure base scenario. For the 3-1 contraflow system two capacities are given. One for the direction with the driving lanes splitting, and one for the direction with a reduced lane width. The capacities for the driving direction with lanes splitting is given to be 3000 veh/h. The direction with a lane width reduction has a capacity of 3400 veh/h. Converted this yields capacities of 3450 pcu/h and 3910 pcu/h. These values are used for the vehicle inputs of the 3-1 contraflow system base scenario. Both networks use the same inputs for all scenarios.

Scenario set-up

As mentioned in section 4.1, two networks are modelled. These networks are the right lane closure and the 3-1 contraflow system. Three types of CAV driving logic, as specified in section 4.2, are modelled. These are the cautious, normal and all knowing driving logic. The CAVs are modelled at five different penetration rates (from 0 to 100%, in steps of 25%). The two base scenarios account for the 0% penetration rates. These scenarios function as a control group. Per network, twelve (three CAVs and four PR%) additional scenarios are created to account for the variations in CAVs and penetration rates. This leads to a total of 26 scenarios that have to be analyzed, as can been seen in figure 4.8. These 26 scenarios are all run 11 times. This is the advised number of runs when including stochastic elements in VISSIM (PTV Group, 2019).

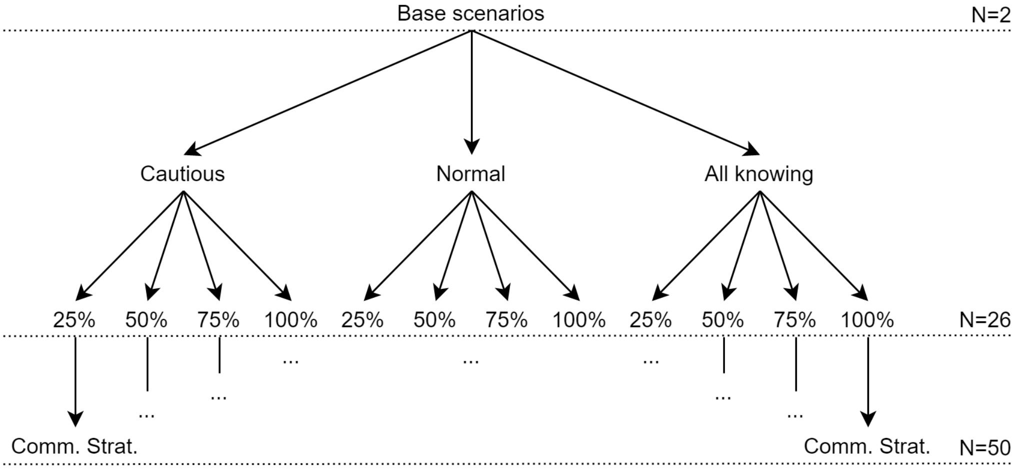


Figure 4.8: Scenario design

After analyzing the first 26 scenarios, the communication strategies that are aimed at aiding traffic efficiency and safety are implemented in the simulation scenarios. What these communication strategies will be depends on the findings after analyzing the first 26 scenarios. Adding these communication strategies to all earlier scenarios (except the 0% penetration rate) leads to 24 additional scenarios being created. In total, this implies running 50 different configurations.

4.4. Key Performance Indicators (KPIs)

In this section the KPIs are presented on which traffic efficiency and traffic safety will be assessed. Penttinen et al. (2019) provides a very extensive set of possible KPIs that can be used for this goal. Although the KPIs are categorizes different in their research, it can still be used to select useful KPIs. The final KPI selection was based on the relevance of the KPIs to road operators and their importance in the traffic simulation analysis. For each KPI a general hypothesis is given as well regarding the effects that CAVs will have. All KPIs are summarized in table 4.5.

Traffic efficiency

As mentioned in section 3.3, traffic efficiency is explained in this study as the extent to which a certain transportation input can meet the travel demand of vehicles in a transportation system. The main consensus is that when all vehicles on the road would be automated, the traffic efficiency there would be optimal. It is also found however that the efficiency will initially worsen with the introduction of automated vehicles. To measure the effects there are several KPIs that could be used. These are presented in the following subsections.

Travel time

The first KPI is the travel time that vehicles experience. Naturally, when the delay as a result of congestion increases the travel time increases. It is expected that when the percentage of CAVs and the level of automation increases, the travel time will decrease. This is expected since the vehicles are expected to react quicker and adapt a shorter headway which leads to a more efficient traffic flow. At lower levels of automation and lower penetration rate it might be that travel times actually increase because of the conservative driving logic that is embedded in the CAVs. As van der Tuin et al. (2020b) mention in their research, travel times differences between scenarios also reflect the road capacity and can be used to assess the impacts of CAVs on the road as the penetration rate increases.

Queue length

The second KPI used to assess the traffic efficiency is the queue length. This KPI is measured throughout the network, but it is expected that the only location where significant queues will form is the road section leading up to the roadwork zone. Additionally, it is expected that when the percentage of CAVs and the level of automation increases the queue length as well as the number of queues that form will decrease. Sometimes small queues might still emerge as a result of merging vehicles that require other vehicles to break. But these small queues will likely dissolve quicker as the CAVs increase in number and automation level. Similar to the travel time and the delay, this KPI also reflects the road capacity.

Driving speed

The average driving speed is the third KPI that is selected. This KPI can be collected on multiple levels. Firstly the speed can be collected per simulation scenario. Secondly it can be collected per vehicle type. This way differences in average speeds can be identified. It is expected that CAVs are able to drive a more constant speed than conventional vehicles, because of the predetermined driving behaviour that is described in literature. Additionally, CAVs are expected to comply with the speed limit better than conventional vehicles. This can result in a lower average speed for the total traffic volume. Although the speed distributions that vehicles use in simulation are an input, the speeds that are actually found in the simulation outputs can still be used as a KPI to map vehicle interactions.

Traffic safety

Connected and Automated Vehicles have been identified in literature as a major opportunity to increase traffic safety. Generally it is assumed that roads will be safer if all vehicles are fully automated. This is due to the elimination of human errors. Safety effects are difficult to model however, since a model will not cause accidents or collisions. Therefore other measures must be used to predict how safe a traffic situation is. As discussed in section 3.4 some studies use SSAM to do this. This method has not been validated fully for CAVs however (van der Tuin et al., 2020b). Therefore this study uses other predictive measures in the same way Smith et al. (2015) propose. The KPIs used to assess the safety in this way are presented below.

Speed variability

Although speed was already selected as a measure for traffic efficiency, it is also chosen to be a measure for safety. Here not the average or absolute speeds, but the speed variability among different vehicles is of interest. It is expected that when CAVs increase in numbers, the speed variability will drop. At higher penetration rates of CAVs the conventional vehicles will also be forced to adapt their driving behaviour. This is because all CAVs will maintain the speed limit. This can lead to large speed differences at lower penetration rates however. Especially the speeds of the conventional vehicles will be of interest in this measure.

Headway

The second KPI that is selected as a measure for traffic safety is the headway. This is the following distance between a vehicle and its preceding vehicle. SWOV Institute for Road Safety Research (2012) finds that headway data is most usefull if it is recorded for vehicles driving over 60 km/h. This will be used in the interpretation of this KPI as well. For automated vehicles it is expected that they will never have a shorter headway than they are told to have. Conventional vehicles tend to keep a smaller headway than legally prescribed quite often however. These phenomena are also expected in the outcomes of the simulation study. CAVs will maintain the headway they are told to maintain where conventional vehicles will vary a lot more. What is most interesting is to see how the headway develops as the penetration rate of CAVs increase. Also the effects of different driving logic are of interest with this measure.

Number of lane changes

The final KPI that is used to assess the traffic safety is the number of lane changes that occurs. This KPI is selected because it is a manoeuvre that is often found to bring along risks. It also is an indication for the variability in speed. Most probably there will be a relation between these two KPIs in the simulation results. It is expected that the least amount of lane changes will occur with 100% CAVs, regardless of the driving logic. This is because these vehicles will have similar driving speeds, so changing lanes is only necessary when lanes cease to continue. As long as conventional vehicles are present there will be vehicles that want to drive above the speed limit which leads to more lane changes.

Table 4.5: Key performance indicators

Category	KPI	Unit
Traffic efficiency	Travel time	[sec]
	Queue length	[m]
	Speed	[km/h]
Traffic safety	Speed variability	[km/h]
	Time headways	[s]
	Lane changes	[#]

5

Results

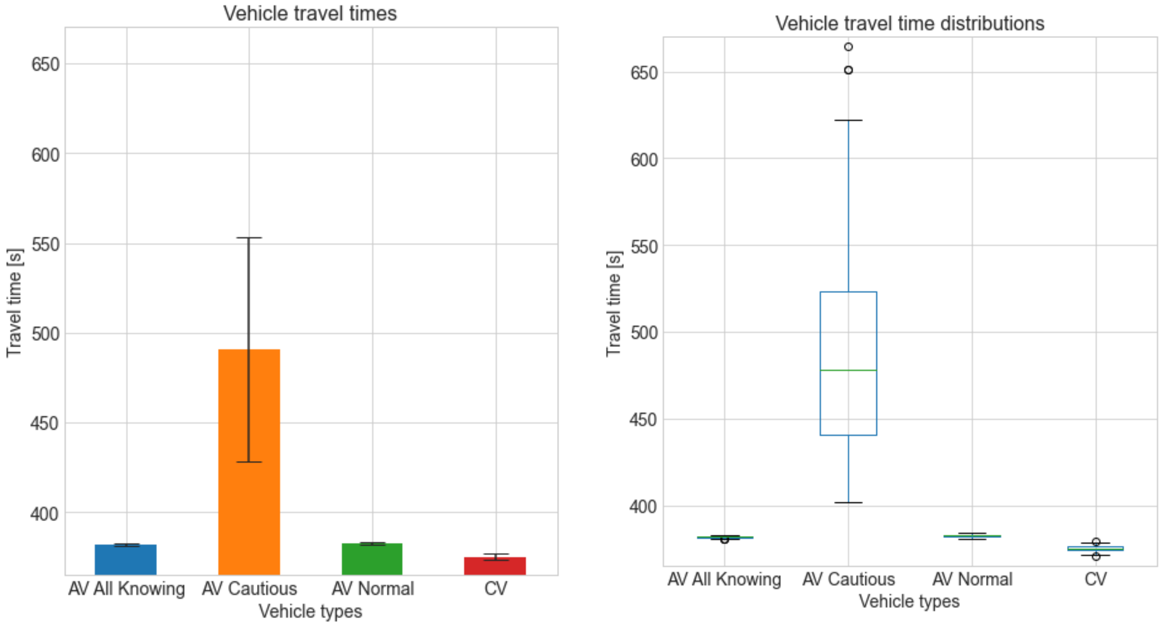
Because the simulation scenarios are divided into two separate networks, the results of the two networks are presented separately as well in this chapter. Sections 5.1 and 5.2 respectively present the results that were found for the right lane closure and the contraflow system. Possible suitable communication strategies are identified and tested in section 5.3 based on the results so far.

5.1. Right lane closure

Traffic efficiency

Travel time

The first results of the simulations that relate to traffic efficiency are presented in figure 5.1. This figure purely shows the effects that the driving logic has on the travel times in the network. To clearly observe the effect of the driving logic, this figure only shows the travel times in the 0% penetration rate scenario, and the 100% penetration rate scenarios of the different CAV types. Note that figure 5.1a shows the travel time averages with standard deviations for the four scenarios. Figure 5.1b shows the distributions of these travel times within these scenarios.



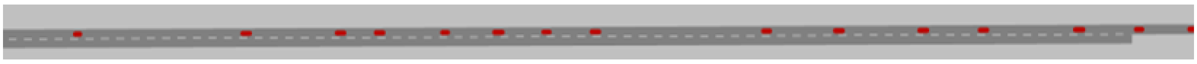
(a) Vehicle travel time averages with standard deviations

(b) Vehicle travel time distributions

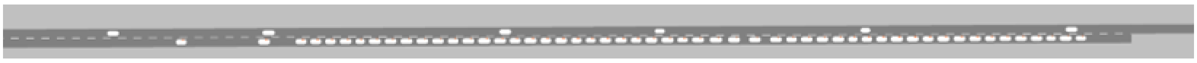
Figure 5.1: Vehicle travel times and distributions at 0% and 100% CAV penetration

What becomes very clear is that the cautious driving behaviour as formulated in chapter 4 results in much longer travel times than the other three behavioural settings. On average, cautious CAVs take 491 seconds to clear the 8km section over which the travel times are measured, while all knowing and normal CAVs only take 382 and 383 seconds to clear this section respectively. With a travel time of 375 seconds the conventional vehicles are the quickest. This can be explained by the desired speed distributions that were presented in section 4.2 where it can be seen that conventional vehicles tend to drive a lot faster than the legal speed limit.

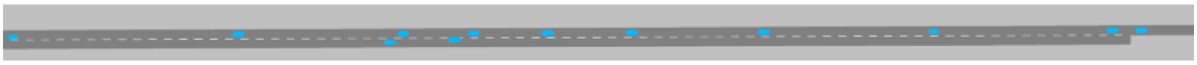
What stands out is that the travel times of cautious CAVs also fluctuate much more than the other three configurations. One would expect that the travel times of the CAVs would fluctuate much less than the travel times of conventional vehicles. This is true for the normal and all knowing CAVs, that only show a standard deviation of 0.7 and a 0.6 seconds compared to a deviation of 1.6 seconds for conventional vehicles. With a standard deviation for cautious CAVs of 62.4 seconds this driving logic behaves quite unexpectedly. Even with congestion, this much deviation is not what one would expect. This is also visible in figure 5.1b that shows that the travel times of cautious vehicles are distributed very wide. Why this is can be seen in figure 5.2.



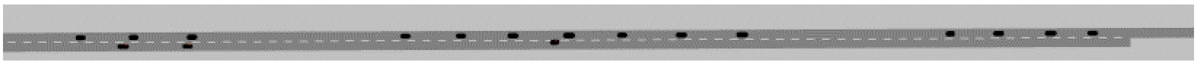
(a) 100% All knowing



(b) 100% Cautious



(c) 100% Normal



(d) Conventional vehicles

Figure 5.2: Screenshots of VISSIM showing the traffic situation right before the bottleneck at a right lane closure

Queue length

Significant queues only form in the scenario with cautious CAVs. This can be seen in figure 5.2b. The congestion that occurs only forms constantly on the right lane. Cautious CAVs enforce the absolute breaking distance and are less smart. This means that their observations while merging are less elaborate. This causes major issues while changing from the right lane to the left lane. Vehicles that are already driving on the left lane do not notice this and continue driving at cruising speed. Only very sporadically does a vehicle manage to switch to the left lane, which causes slight congestion on the left lane as well. This congestion dissolves quite quickly after which the traffic state that the image shows continues again.

How these queues form during the simulations as penetration rates increase is presented in figure 5.3. This figure present the average queue length on the road section before the bottleneck over the different runs. It also shows the standard deviations. What becomes clear is that as the penetration rate of cautious CAVs increases in the simulations, the queues that form become longer over time. The vehicles with conventional driving logic do not get caught up in this congestion for the most part. The individual vehicles that do, only stay in the queue for a short time. This is because they have less difficulty with merging in smaller gaps. It can be seen in this figure, and in earlier results, that in simulations with 0% CAV penetration rate no significant congestion forms. This is also true for simulations with only normal or all knowing CAVs. Therefore they are excluded from figure 5.3. In the simulations with 25% cautious CAVs small queues form in front of the bottleneck. In the scenarios with 50% and 75% cautious CAVs the queue in front of the bottleneck increases initially, but stays relatively constant in length when it reaches a certain length. This is a result of the penetration rate and the way in which the vehicles are distributed over the two lanes. At 50% penetration rate the queue stays relatively constant after reaching 400 meters, and at 75% penetration this tipping point lies at approximately 570 meters. When this tipping point is reached, it can be seen that the deviations of the queue length decreases. In the simulations, this tipping point is not reached for the 100% penetration rate within the 1 hour simulation time. Therefore the queue length is still increasing. The standard deviations keep increasing as well. If the simulation time would be longer both the average queue length as well as the standard deviations of the queue length would keep increasing because the cautious CAVs will continue having trouble switching lanes.

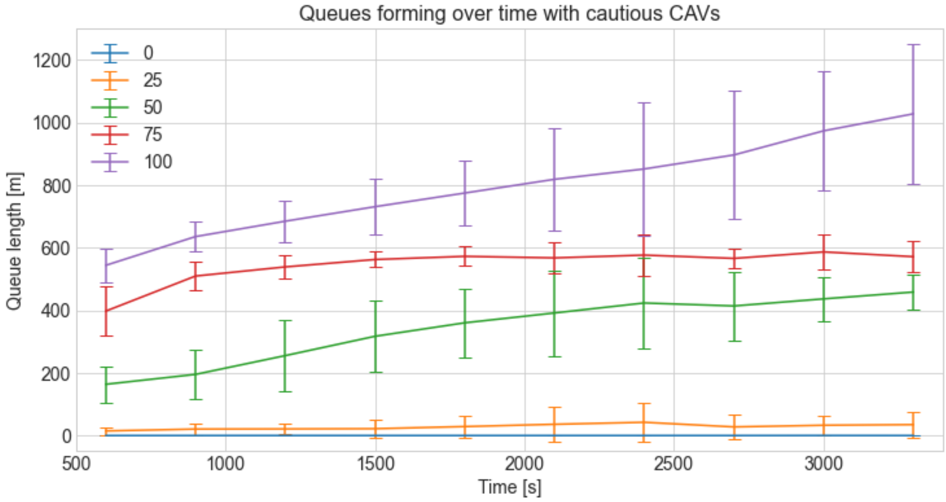


Figure 5.3: Queues forming over time with cautious CAVs

Speeds

The forming of queues naturally has major implications for the driving speeds that are reached by the different vehicle types in the simulations. In figure 5.4 the distribution of the driving speeds of vehicles on the road section before the roadwork zone begins are recorded. Later in this section the speeds within the work zone are discussed. This histogram is divided into 100 bins that are subsequently grouped by vehicle type. Note that this figure does not differentiate between the different penetration rate scenarios. This is also the reason why the conventional vehicles make up a larger part of the histogram than the other three vehicle types because they are present in all scenarios except for the 100% CAV scenarios.

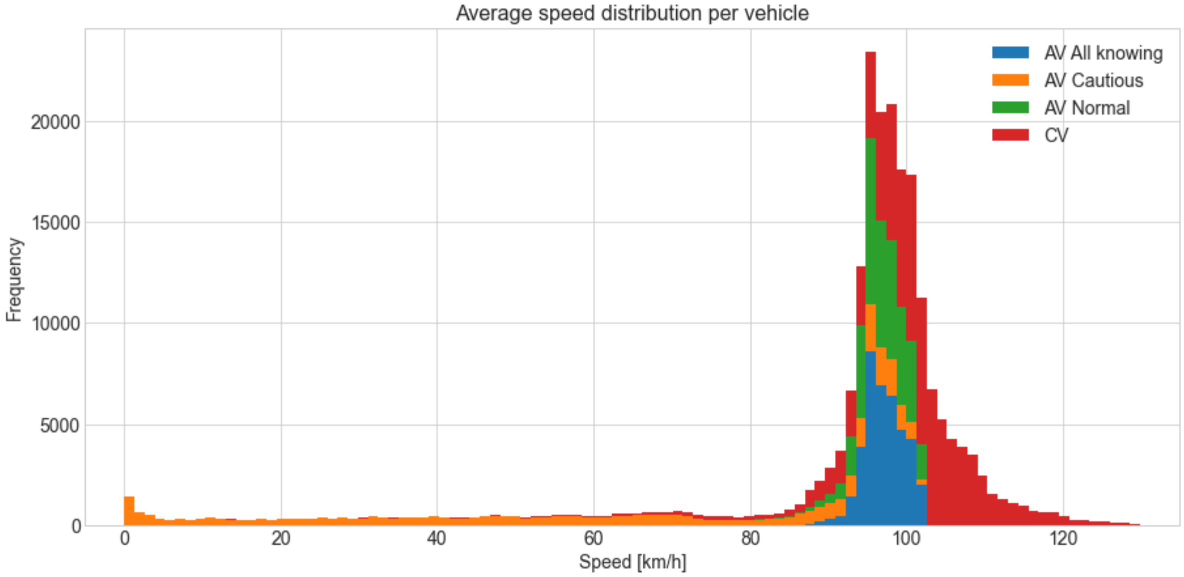


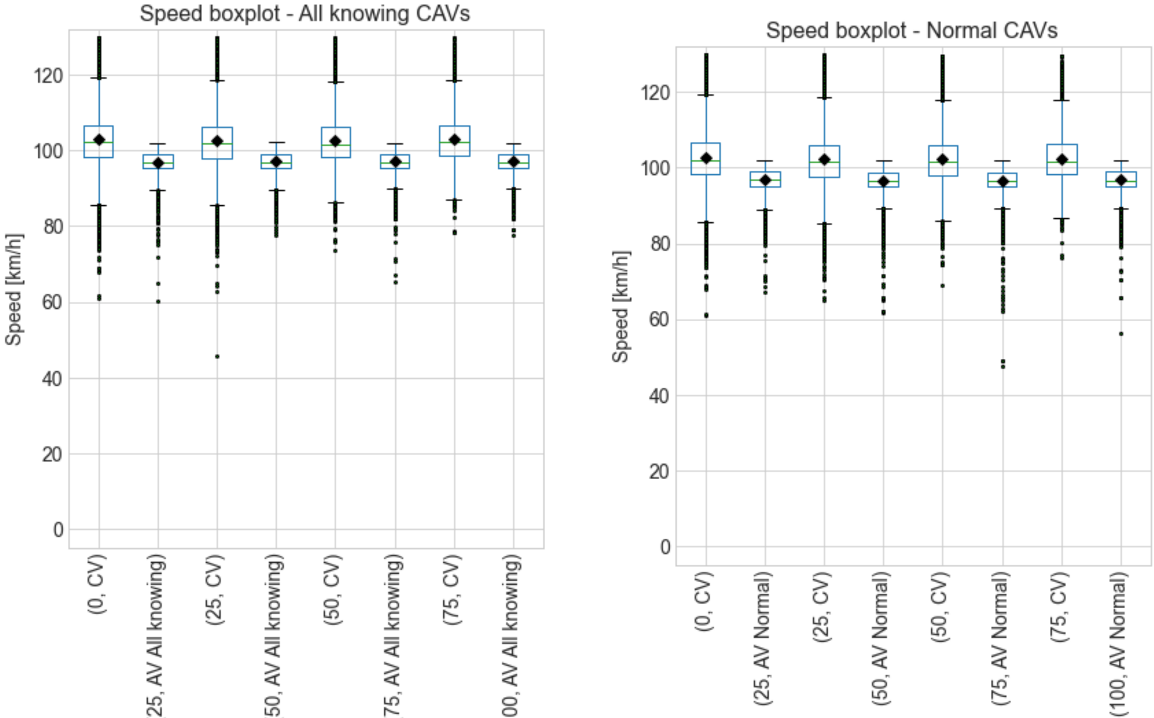
Figure 5.4: Average driving speeds of different vehicle types on the road section right before the right lane closure

As could be expected based on the results so far, the cautious CAVs cause the figure to be skewed towards the lower driving speeds, while the other two CAV types appear to be distributed normally, although no statistical test is executed to check this. On average vehicles drive 91.2 km/h on this section of road with a standard deviation of 22.3 km/h. This is quite a large deviation that can be explained by two observations. The first is of course the large tail on the left side of the distribution. The 25th percentile lies at 93.5 km/h. The group of vehicles below this speed consists almost exclusively of cautious CAVs, with only very few conventional vehicles being part of this group. The other observation is the large part of conventional vehicles that drive over the speed limit. The 75th percentile starts at 100.8 km/h. This means that 25% of these vehicles drive faster than the legal speed limit of 100 km/h. The maximum recorded average speed over the segment is 129.9 km/h. All vehicles within this top 25% are conventional vehicles. This vehicle behaviour is a result of the desired speed distributions that were discussed in chapter 4. The all knowing and normal CAVs are distributed around the speed limit quite well with the lion's share being right around the the median(50% mark) of 97.3 km/h.

A more detailed look at the effects the CAVs have on how the speeds of the individual vehicle types is presented in figure 5.5. The top two figures show the speed boxplots of the scenarios with all knowing CAVs and normal CAVs. These are presented side-by-side since they are very similar. The bottom figure shows the boxplots of the scenarios with cautious CAVs. This y-axis represents the speed distributions. The x-axis is presented in two parts. The number (e.g. 25) represents the CAV penetration rate in that scenario. The vehicle type behind this number represents the type of vehicle the distribution is presented for. Individual plots are made for the CAVs and CVs per penetration rate scenario. The small diamond within each boxplot represents the mean driving speed, and the dots represent outliers in the data (outer .7% of data) in addition to the regular information a boxplot already provides by default.

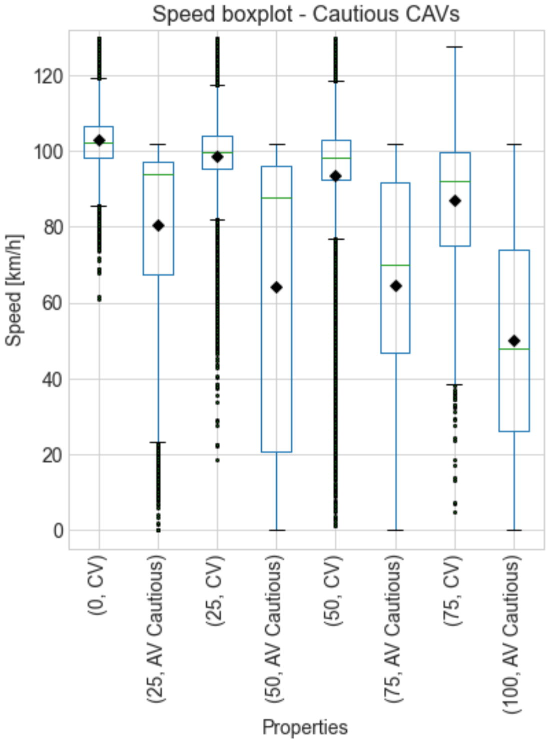
When comparing the three images with each other, the first thing that stands out is that the two figures 5.5a and 5.5b look very much alike, but very different from figure 5.5c. This third image will therefore be discussed separately. In figure 5.5a and 5.5b the exact same observations can be made. Conventional vehicles are spread a bit more than CAVs in terms of speed. As the share of CAVs increases, the speed distributions of conventional vehicles do not really change. Averages remain the same or are only reduced very little. The outliers that are present on the bottom of the boxplots become less common. When looking at the outliers for CVs above at the top of the boxplot it can be seen that here too they become less common. Especially with normal CAVs the speed distribution of CVs is at bit more centralized, although this effect is only marginal. As the CAVs in these two figures represent a larger part of traffic, the speed distributions become more centralized. CAVs do not have any outliers in the top section of the boxplot, since their driving logic does not allow for speeding. The outliers in the bottom of the boxplot become less frequent as the penetration rate increases. This suggests that interactions between CAVs and CVs are not always smooth. Finally, CAVs generally drive slower than the CVs as a result of their speed distributions. As CAVs represent a larger share of traffic, the average speeds of the total traffic system will therefore be reduced, although the speeds distributions of CAVs and CVs do not change that much over the different penetration rates.

The effects of the cautious driving behaviour on the speed distributions in figure 5.5c are quite severe. As the penetration rate of CAVs increases, both vehicle types perform worse in terms of speed. At a 25% penetration rate the speed of conventional vehicles is spread much more compared to 0%, although here this effects can mostly be noticed in the increase in outliers. The whiskers are not spread much wider. The distribution of the CAVs is already very skewed at 25%, with quite some vehicles that experience significant congestion. This effect worsens when the penetration rate is increased to 50%. The speeds of CAVs drop, and this has a big effect on the speed distribution of CVs as well. What stands out is that the 50% of the CAVs with the highest speeds is still able to drive relatively fast (around 90 km/h). This can be explained because in the simulations, the persistent congestion mostly forms on the right lane. Vehicles on the left lane experience only minor effects of this. This also explains why the negative effects on the speeds of CVs remain relatively marginal. CVs are usually able to switch lanes in time and pass the queue. The average speeds of CVs is significantly lower with higher CAV penetration rates however. With a 75% CAV penetration rate the congestion caused by the cautious CAVs has significant effects on the speed distribution. The median drops severely, as well as the mean speed. In general, the speeds of CVs are much more spread. The speeds of CAVs are less spread than they are at 50% penetration rate, but lower in general. At 100% CAVs the vehicle speeds are distributed normally, but the speeds are generally low at around 50 km/h.



(a) All knowing CAVs and CVs

(b) Normal CAVs and CVs



(c) Cautious CAVs and CVs

Figure 5.5: Speed boxplots grouped by vehicle type and penetration rate on the road section right before the right lane closure

The speed distribution within the work zone itself looks very different. A histogram of these speeds is presented in figure 5.6. The speeds are distributed much more normally than those in figure 5.4, although in this instance slightly skewed toward the higher driving speeds. On average the vehicles drive at a speed of 69.1 km/h over the work zone trajectory. The speed limit in this area is 70 km/h so this makes sense. Vehicles are not able to overtake within the work zone since it only consists of one lane. This means that the vehicles that want to drive over this limit are limited by other vehicles that do want to stick to this limit. The peak of the distribution lies at 68.9 km/h. The interquartile range, difference between the 25th and 75th percentile ranges from 68.4 km/h to 69.6 km/h. This shows that the distribution is very centralized. Both the minimum and the maximum fall outside of the chosen range of figure 5.6, because these are outliers and would not be noticeable in the figure since they only appear once. The minimum lies at 39.4 km/h and the maximum at 86.8 km/h. The steep angle that can be seen around 68 km/h can be explained by the speed distribution of all vehicles. For both CAVs and CVs the minimum desired speed at a legal speed limit of 70 km/h lies at 68 km/h. All data points below this speed are caused by irregularities in traffic. The longer tail on the right side of the distribution, that causes the distribution to be skewed, is caused by the combination of two factors. The first factor is that vehicles that enter the work zone are only told to drive at 70 km/h once they enter the work zone. This causes that vehicles are still slowing down from the 90 km/h to 70 km/h in the first section of the work zone. The second factor is fact that the desired speed of CVs is distributed more at higher speeds. This makes that the average speed of CVs over the entire trajectory tends to be higher than the speeds of CAVs, and thus causes the skewedness.

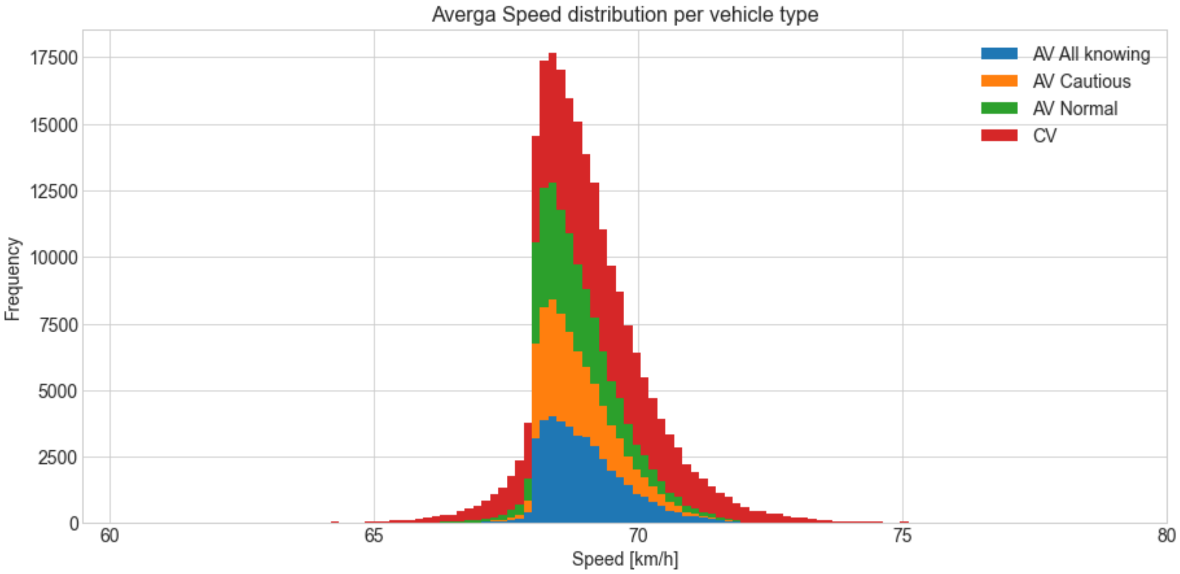
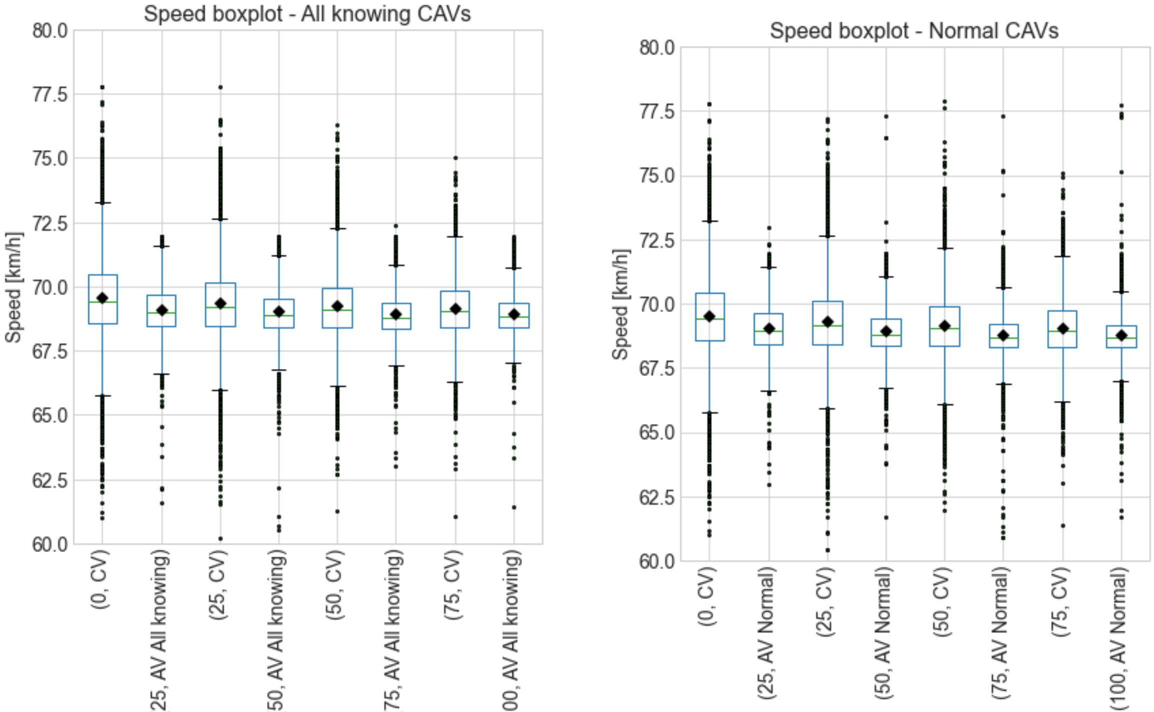


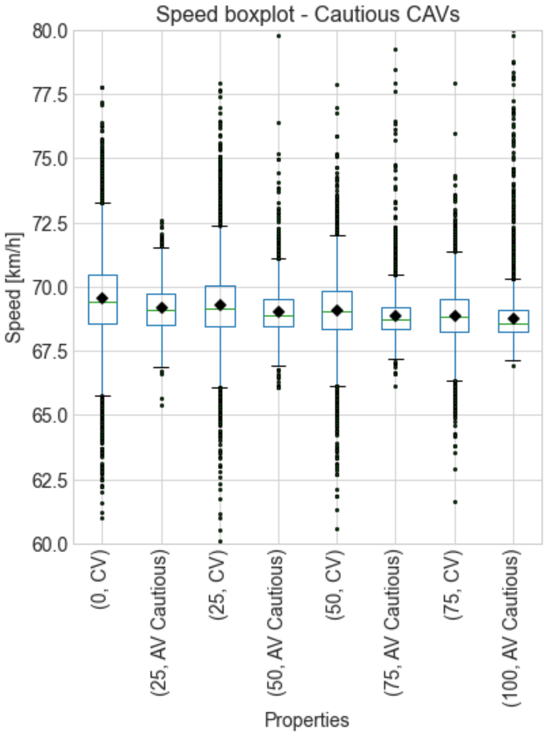
Figure 5.6: Average driving speeds of different vehicle types on the road section within the right lane closure work zone

A more detailed representation of the effects of the CAVs on the driving speeds withing the work zone is provided in figure 5.7. Note that the vertical axes only ranges from 60 km/h to 80 km/h here to make differences between the boxplots more visible. All distributions are relatively small, as could be expected based on figure 5.6. This is a result of the fact that this part of the network only consists of one lane which reduces irregularities in traffic. When looking at the median and the average speeds, it can be noted that the three different CAVs have similar effects. As the penetration rates of CAVs increase, the overall speeds are reduced although this effect is very small. The distributions of CVs become slightly more centralized. The percentiles follow this trend as well. Big differences between the vehicle types can be spotted when looking at the outliers. The outliers above the CV boxplots are caused by two factors. The first is that they are still slowing down from the 90 km/h to 70 km/h in the first section of the work zone. The second factor is that when a vehicle has no vehicle driving in front of it, the vehicle will try to reach its desired driving speed until it reaches another vehicle that drives slower. In the early stages of the simulations, and with lower CAV penetration rates, some CVs are able to reach these higher speeds.



(a) All knowing CAVs and CVs

(b) Normal CAVs and CVs



(c) Cautious CAVs and CVs

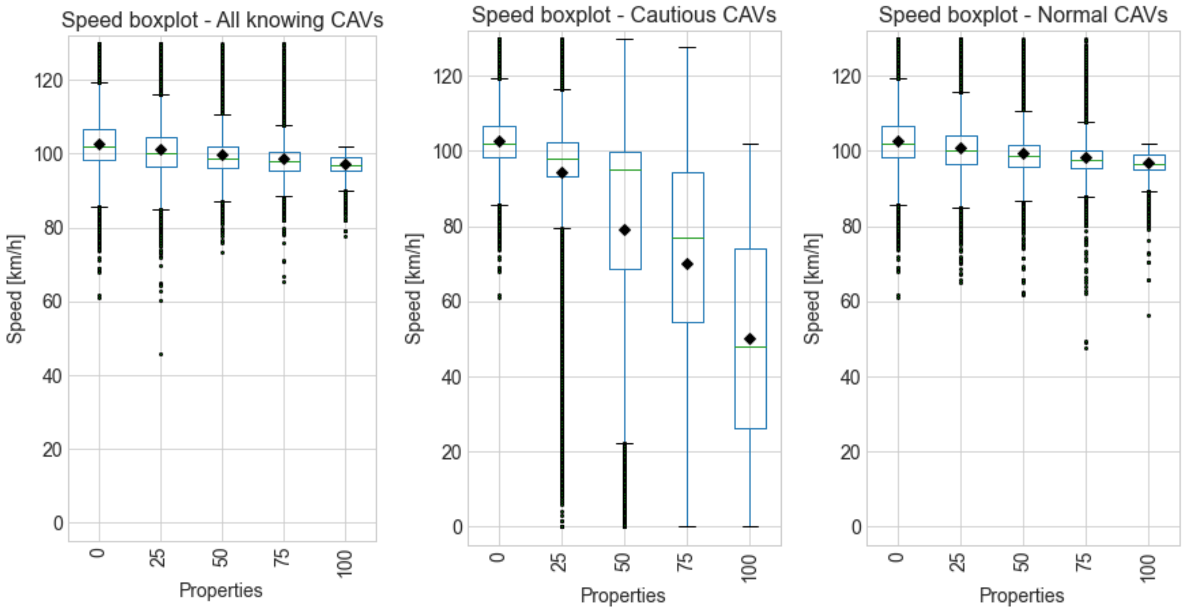
Figure 5.7: Speed boxplots grouped by vehicle type and penetration rate on the road section within the right lane closure

The upper outliers that occur at the CAV boxplots are only the result of the vehicles slowing down. The differences in the occurrence of these outliers is quite large when comparing the three CAV types . This can be explained by the speed at which the CAVs slow down. All knowing CAVs tend to slow down very quickly, as was shown in table 4.2. This means that their average speed over the entire work zone section is only slightly influenced by the first deceleration section. Normal CAVs tend to brake slightly less hard. Cautious CAVs brake very slowly, especially when in close vicinity with other vehicles as to not cause any risk for surrounding traffic. This is clearly visible in figure 5.7c. The lower outliers are caused by irregularities in traffic. These are caused by vehicles driving too close to each other. When braking is then required, other vehicles have to brake as well. This leads to a chain reaction. As can be seen when comparing the three figures, these lower driving speeds appear less frequent as the penetration rate increases. Normal CAVs cause slightly more of these lower driving speeds than all knowing CAVs. Cautious CAVs cause only very little low driving speeds.

Traffic safety

Speed variability

In order to assess the traffic safety of the total traffic situation based on the speed variability, the figures that were presented in the previous section are altered and grouped per scenario in figure 5.8. Figure 5.5 and 5.7 are used as well. The effects on the speed, as well as the distributions have been discussed earlier. Here the focus only lies on what this means for all traffic participants combined. The speed is again first discussed for the road section ahead of the work zone, and then for the road section within the work zone itself since these two section differ severely. Figure 5.8 only present the speed variability on the section before the work zone.



(a) All knowing

(b) Cautious

(c) Normal

Figure 5.8: Speed variability boxplots grouped by scenario on the road section right before the right lane closure

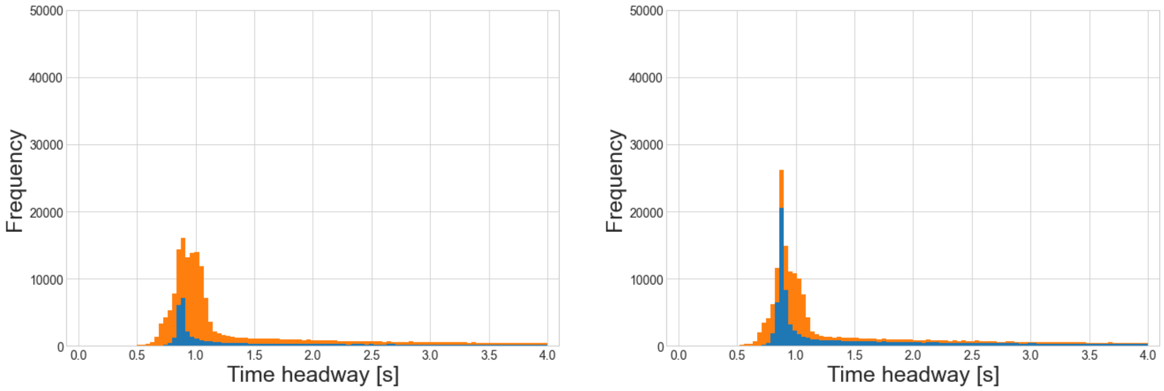
Implementation of normal and all knowing CAVs generally makes the traffic situation in the simulations safer in terms of speed. Speeds are slightly lower, which is known to be safer as it reduces the crash severity. This effect is almost negligible however. The greatest effects are noticeable in terms of speed variability. As these CAV types increase in share, the general speed variability is vastly reduced. This is not the result of changes to the driving behaviour of CVs however, as seen in figure 5.5a and 5.5b. Here it can be seen that the distributions of CVs bare change when the share of CAVs increases. The amount outliers are a bit reduced, but this is not a huge effect. The change in distribution that can be seen in figure 5.8a and 5.8c can thus mostly be explained by the increased share of CAVs. This share makes that overall the driving speeds become more homogeneous, and therefore safer, but the behaviour of CVs remains mostly the same.

The implementation of cautious CAVs makes the traffic situation more unsafe in the simulations in terms of speed. As is clearly visible in figure 5.8b, the speed variability increases as the share of CAVs increases. Additionally, congestion only forms on the right lane while vehicles on the left lane continue to drive at relatively high speeds. This makes the severity of a potential crash high.

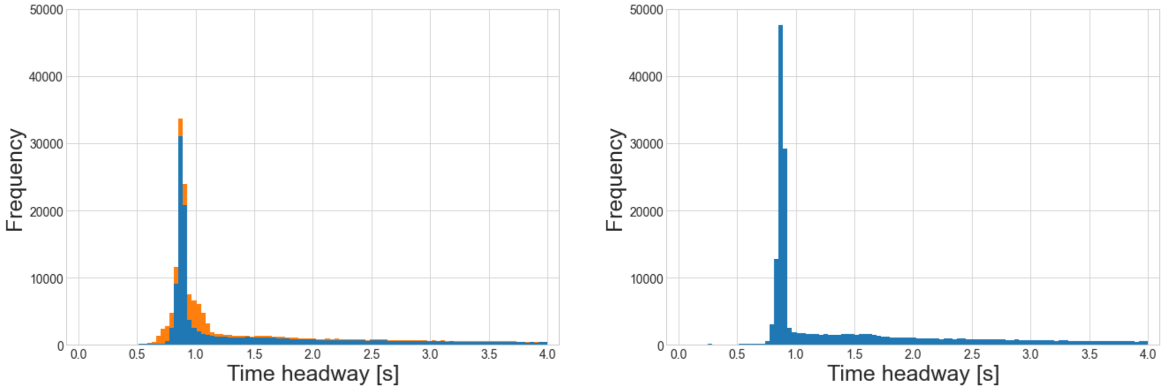
When assessing the effects of the CAVs on speed variability within the work zone itself, the figures shown in figure 5.7 can be used. As mentioned before, the speed variability is reduced for all types of CAVs as they represent a larger share of traffic. Since this section only consist of one lane, the effects of the CAVs on the driving of CVs are much larger here than in the road section before the work zone. This means that the speed variability of CVs is also reduced as CAVs increase. The distributions of the normal CAVs show the most outliers of the three CAV types. This is a result of their braking behaviour early in the work zone section.

Time headways

For the assessment of safety based on vehicle time headways, only those headways that are maintained at higher speeds are of interest. This is why the data in this section has been filtered to only include headway data points that were observed above the 60 km/h mark. The time headways have been plotted in the figures 5.9 and 5.10. Since the headway distributions of normal and all knowing CAVs were very similar, the decision was made not to show the stacked frequency plots of normal CAV scenarios as this would not add any new information. The orange bars represent conventional vehicles and the blue bars represent the CAVs.



(a) 25% all knowing (b) 50% all knowing

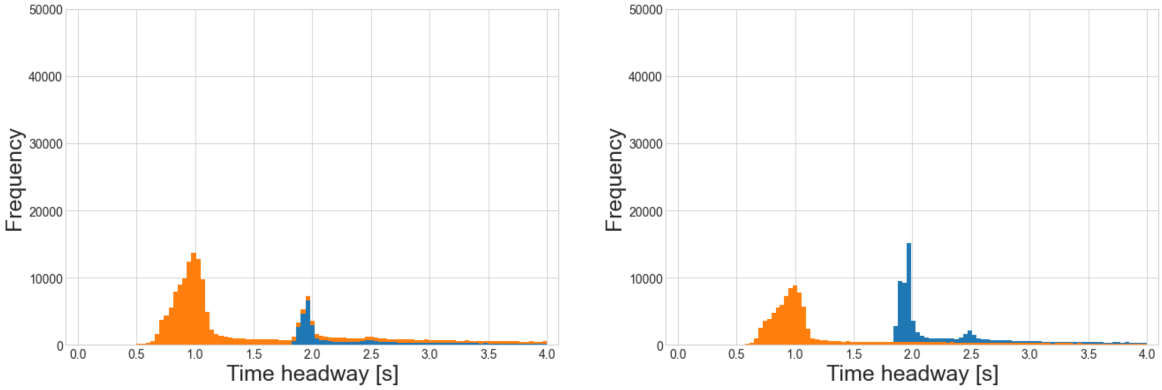


(c) 75% all knowing (d) 100% all knowing

Figure 5.9: Frequency plot of simulated time headway observations at different penetration rates of all knowing CAVs (blue) in combination with conventional vehicles (orange)

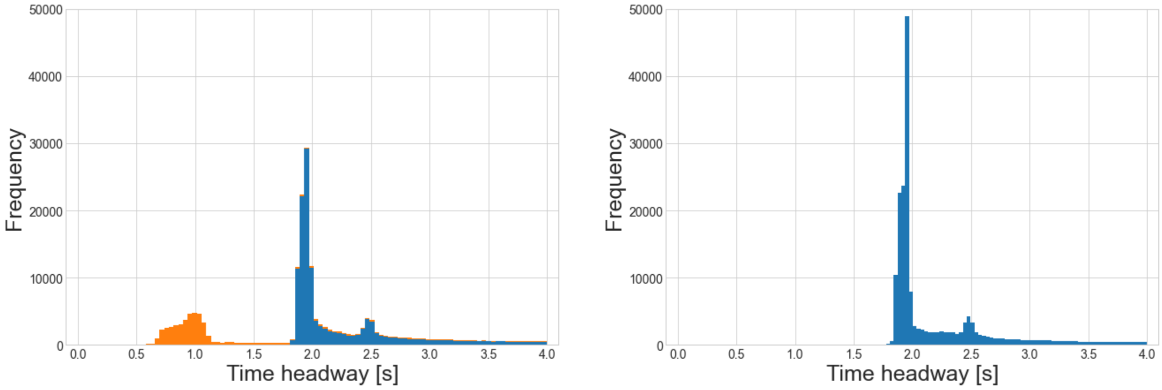
As can be seen in figure 5.9, the CAVs are distributed very consistently among the different penetration rate scenarios. Most all knowing CAVs are recorded to maintain a time headway of 0.9 seconds. These are very short headways considering SWOV Institute for Road Safety Research (2012) mentions an average braking time of 6 seconds at these speeds. There are many CAVs that keep longer time headways. This is visualized by the long tail on the right side of the peak value. The vehicles maintaining headway longer than 4 seconds are left out of the figure. Some vehicles were also recorded to maintain a headway even shorter than 0.9 seconds. Because these appear so little, it is hard to notice these vehicles in the figures. In figure 5.9d a small bar can be noticed representing vehicles with a time headway of only 0.25 seconds. Upon visual inspection of the simulations, it was noticed that these short headways occurred quite regularly. When these vehicles transition into a road section with a lower speed limit then they are currently driving, while driving close to a preceding vehicle, this leads to dangerously short headways. The preceding vehicle brakes, and every vehicle behind it has to brake as well which leads to headways of up to 0.2 seconds at speeds of 90 km/h.

The headways of CVs are more distributed. The absolute number of CVs that keep a short headway is reduced as the penetration rate of CAVs increases. This is due to the fact that there are less CVs present. This has to be noted. What can be seen is that the time headway distribution remains mostly the same. The time headways of CVs are distributed around the 0.95 seconds mark. The distributions is wider than the distribution of CAVs. In the speed range between these two values CVs tend to show most outliers. CVs generally tend to maintain a longer time headway than CAVs, although there are also many CVs that do maintain a shorter headway. Visual inspection of the simulations showed that this mainly occurred when merging. Similar to the CAV distribution, the CVs also show a large tail on the right side of the peak. Although the number of outliers that keep a very short headway is reduced as CAVs increase, the shortest headways remain the same at 0.5 seconds.



(a) 25% cautious

(b) 50% cautious



(c) 75% cautious

(d) 100% cautious

Figure 5.10: Frequency plot of simulated time headway observations at different penetration rates of cautious CAVs (blue) in combination with conventional vehicles (orange)

The normal CAVs, that are not shown in a figure, show similar time headway distributions of CVs and CAVs as those shown by all knowing CAVs. The peak for these CAVs lies at 1.2 seconds, and is the same for CVs. The normal CAVs themselves maintain a longer headway than the all knowing CAVs as a result of their settings. Normal CAVs generally maintain a minimal time headway of 1 second. The distribution of CVs is the same with normal CAVs as it was with all knowing CAVs.

Cautious CAVs keep a much longer headway than the other two CAV configurations. This is what was expected. Most cautious CAVs maintain a time headway of 2 seconds. This is more than double the headway of a normal and all knowing CAV. What stands out however is that the headway distribution shows a second peak at 2.5 seconds. This seems to indicate the the ”enforce absolute braking distance” feature that is enabled for cautious CAVs is the limiting factor for maintaining headway instead of the ”minimal headway”. This would lead to the second peak, because the absolute braking distance is different at different speeds. Seeing that the simulations contain two large areas where the same speed limit applies(100 km/h and 70 km/h), this would lead to two peaks. One should keep in mind that, as a result of the congestion that forms, many cautious CAVs drive too slow in the area ahead of the work zone for their headway data to be included in this analysis.

As can be seen in figure 5.10, the headways that are maintained by CVs are very similar when comparing the scenarios with cautious CAVs and all knowing CAVs with each other. When comparing the effects of the 75% CAV penetration rate of cautious and all knowing CAV with each other, the headways maintained by CVs with cautious CAVs generally are slightly longer than those of CVs with all knowing CAVs. This is most likely due to the fact that not many cautious CAVs are able to enter the area with reduced driving speeds smoothly due to the congestion that was found to form in figure 5.3.

Lane changes

As was mentioned in chapter 3, the amount of lane changes that take place can be used as an indicator for traffic safety since it is a manoeuvre that causes risks. In the simulations, lane changes only take place on the road sections before and after the work zone. In this analysis, only the lane changes before the work zone are taken into account, since this is the part of the network with the highest risks. The lane changes per scenario are presented in figure 5.11. These are not subdivided by vehicle type per scenario.

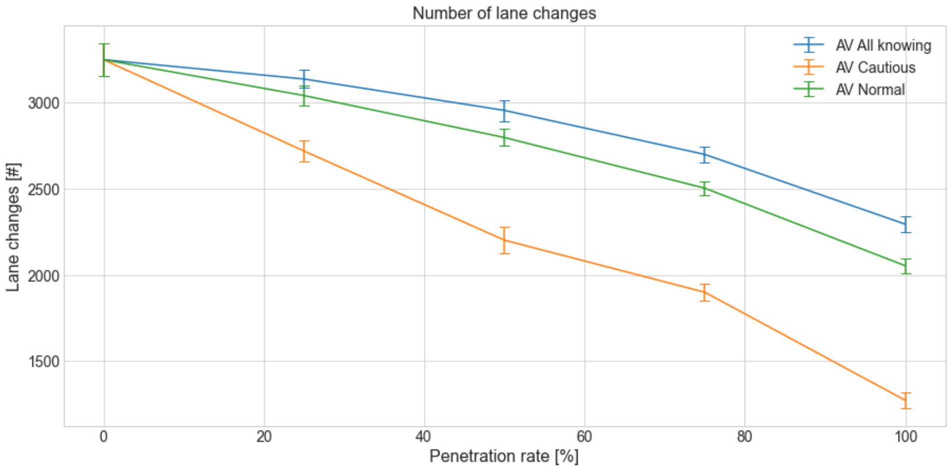


Figure 5.11: Number of lane changes that take place on the entire road section before the work zone per scenario

As CAVs increase, the amount of lane changes that take place in the simulations decrease. This is true for all CAV types. With 100% CVs the number of lane changes was on average 3250 per simulation run with a standard deviation of 95 lane changes. As CAVs increase the standard deviations are always found to be lower in the simulations. This can be explained by the fact that CAVs behaviour is more deterministic than that of CVs. The simulation runs therefore show less differences in terms of lane changes.

There is a difference in the degree and the cause of the reduction of lane changes. As seen earlier, the speed distributions become more centralized as the penetration rate of CAVs increases. This means that overtaking happens less often which leads to fewer lane changes taking place to overtake. Because vehicles tend to drive in the right lane when they are not overtaking, the CVs that drive an above average speed stick to the left lane where they can overtake. The slower CVs simply drive on the right lane between the CAVs. These conventional vehicles do therefore not change lanes as often. The difference between the effects of different CAV types can mainly be explained by the lane changing capabilities of the different types. The cautious CAVs are simply not able to change lanes most of the time. This explains why the number of lane changes taking place is only 1271. The average number of lane changes taking place with only normal or all knowing CAVs is 2053 and 2294 respectively. These vehicles are able to make lane changes, with the all knowing CAVs working cooperatively to let each vehicle change lanes. This means that they are able to make these changes more easily which explains the difference between the two. The standard deviations are almost halved to 45 for cautious CAVs, and 46 and 43 for all knowing and normal CAVs.

Summary

The effects of different types of CAVs on the traffic efficiency in the right lane closure simulations vary from one another. Cautious CAVs have the biggest negative effects. Travel times are extremely increased as these CAVs increase in number. This is a result of the large queues that form ahead of the bottleneck because these vehicles have difficulties changing lanes in busy traffic. This automatically leads to lower observer average speeds on this road section and also affects the traffic efficiency of the CVs in these scenarios. Normal and All knowing CAVs generally do not experience any difficulties transitioning from 2 lanes to 1 lane. Even those individual vehicles that do fail to change lanes initially because they are surrounded by traffic, find a way to merge once they get the chance. This makes that the travel times of traffic with these two CAV types are only slightly longer than those in a purely conventional scenario. No significant persisting queues are formed. The average speeds do slightly drop, but this is a result of the assumption that CAVs stick to the speed limit where CVs more often drive over the limit. Within the work zone itself the three CAVs have the same effects on traffic. Travel times and average speeds are slightly reduced, and no queues form. CVs have to adapt their driving speeds to the CAVs which lead to more homogeneous driving speeds across the board.

The effects of the CAVs on safety vary as well when looking at the KPIs. The speed variability is reduced with increasing normal and all knowing CAV penetration rates. Especially on the road section right before the work zone this is noticeable, but also inside the work zone traffic speeds are more homogeneous. Cautious CAVs only increase the speed variability near the bottleneck however. The congestion forming on the right lane, with traffic on the left lane driving at relatively high speeds leads to a very high variability and dangerous speed differences between vehicles. All three CAV types do not alter the way in which the time headway distribution is shaped noticeably. With low penetration rates there is a larger number of CVs that maintain a short headway than with higher penetration rates. What does stand out is that the normal and all knowing CAVs themselves maintain a dangerously low headway in transition sections where the speed limit is reduced. This is a result of these CAVs keeping a shorter headway in general. Cautious CAVs keep a very long headway. The number of lane changes that occur per simulation run is severely reduced as the CAV penetration rate increases. For cautious CAVs this is mostly due to the CAVs not being capable of a lane changes in congested areas. For normal and all knowing CAVs this is due to the speeds being more homogeneous among vehicles.

Some of the effects could have been expected beforehand. Especially the effects of CAVs on the average time headway and speed and speed variability could have been predicted because they are a direct result of the behavioural settings of CAVs. This relates to the setting of the minimal headway and the speed distributions. The travel time is a derivative of speed, but it is also influenced by factors such as queues. The effects of CAVs on the travel times could therefore not have been expected entirely. The effects of CAVs on queue lengths and the number of lane changes could not have been predicted fully either.

5.2. Contraflow system

The effects that are observed in the 3-1 contraflow system network scenarios are very similar to the results discussed so far. It is for this reason that the decision is made not to elaborately discuss these results. Instead, only the general effects that were observed are discussed here. The figures from which these results are derived are presented in Appendix D.

The effects of different CAV types on the traffic efficiency in the contraflow system are very comparable to those in the right lane closure. The travel times in the cautious CAV scenario are longer than those in the normal and all knowing CAV scenarios. The scenario with 100% conventional vehicles has the shortest travel times. The differences between scenarios are not as big however, because no congestion forms in any of them. The reason for this is that there is no bottleneck in the contraflow network. The road splits up from one 2-lane road into two 1-lane roads with a lane width reduction. The effect of this lane width reduction is negligible however, thus capacity is not reduced. This also results in the travel speeds being very normally distributed for all scenarios. On average the cautious CAVs drive at a lower speed than the normal and all knowing CAVs, and the CVs are the fastest. This is again in line with the results that were found in the right lane closure network.

The effects of the CAVs on the speed variability are similar to the effects observed in the right lane closure. As the penetration rates of the different CAV types increase, the speeds become more homogeneous. As CAVs increase the speed distributions become more centralized around a slightly lower mean. The speed variability is reduced more with normal and all knowing CAVs than with cautious CAVs. All three CAV types do not alter the way in which the time headway distribution is shaped significantly. With low penetration rates there is a large number of CVs that maintain a dangerously short headway that is below the distribution. These cases are less frequent and less severe at higher penetration rates. The short headways that the CAVs themselves maintain are less frequent in this network than in the right lane closure simulations. This can be explained by the design of the work zone. There are fewer speed reductions embedded in this design. As the CAVs increase in number, the number of lane changes that takes place is reduced. The degree of this reduction is in line with the lane changing settings of the CAVs. The cautious CAVs change lanes the least and all knowing CAVs change lanes the most. This is again in line with the findings from the right lane closure simulations.

5.3. Communication strategies

In analyzing the results of the simulations, two main undesirable outcomes were found related to the behaviour shown by the CAVs. The first undesirable outcome is that the cautious CAVs have great difficulties with merging to pass through the bottleneck that is at the beginning of the work zone in the right lane closure scenario. This leads to large queues forming in front of the work zone. The second undesirable outcome is that vehicles drive in very close proximity at the start of the work zone in both network scenarios. This is a result of the speed reductions and the fact that vehicles can no longer overtake each other. To alleviate these negative effects, two traffic measures are formulated. Because both undesirable behavioural outcomes appear in the right lane closure network, the traffic measure are implemented in these scenarios.

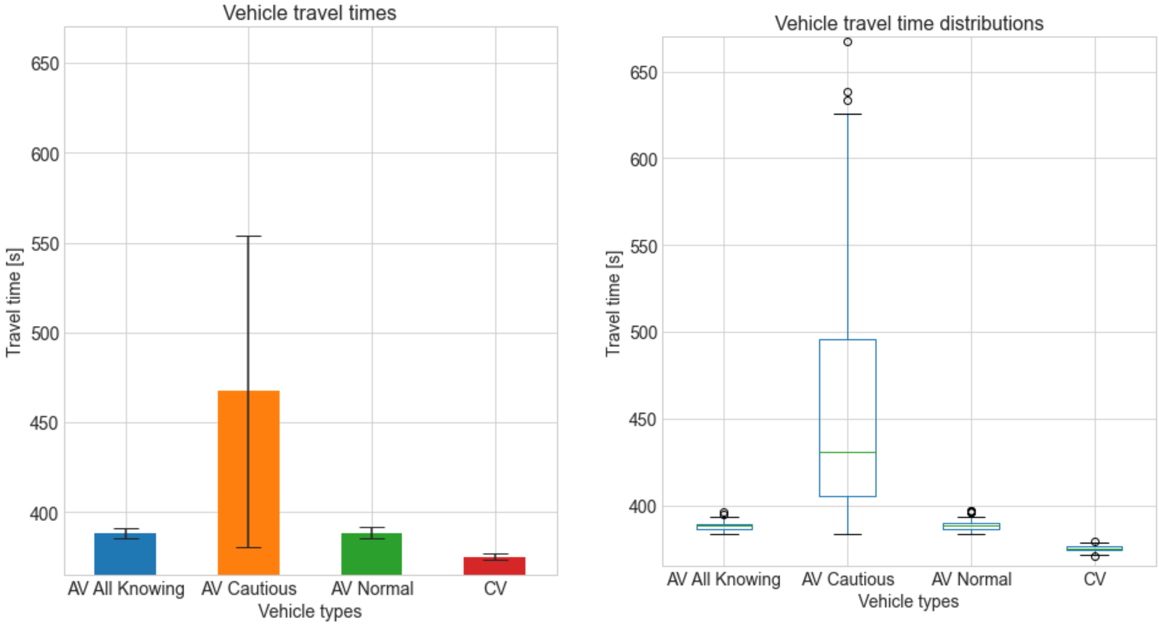
The first measure, that is aimed at alleviating the queues that form in front of the work zone, is a communication measure that tells CAVs to change lanes because a work zone is ahead. This measure is based on finding by van der Tuin et al. (2020b). In their research a similar communication strategy is used that forces CAVs to merge early to pass by a moving work zone. A negative result of this measure is that the CAVs then make it difficult for conventional vehicles to merge, which creates new congestion issues. To prevent this, the measure that is used in this research takes a slightly different approach. The communication is still only aimed at CAVs, similar to the communication used by van der Tuin et al., but CAVs are not forced to merge immediately. They are told 2 kilometers ahead of the work zone that they will need to switch to the left lane when they can. They do not have to do this immediately. This should still allow conventional vehicles and other CAVs to merge as well, especially since cautious CAVs maintain a long headway and normal and all knowing CAVs allow cooperative merging.

The second measure, that is aimed at preventing dangerously short headways, slightly alters the behaviour of CAVs. Because the normal and all knowing CAVs maintain a very short headway of less than 1 second, braking causes following vehicles to brake harder. In reality this could cause accidents. To increase safety, CAVs receive a signal 500 meters ahead of the work zone to adapt the base headway of cautious CAVs. These CAVs maintain a headway of 1,5 seconds, which leads to a more gradual transition into reduced speed areas. This measure is implemented together with the first measure. The results of these measures are discussed in the following sections.

Traffic efficiency

Travel time

The implementation of the communication strategies affects the general travel times in different amounts. Similar to figure 5.1 the travel times and distributions per vehicle type are presented in figure 5.12. The travel times are very similar, although slightly different. What is found in the simulations is that the average travel times in the cautious CAVs scenarios are reduced from 491 seconds to 468 seconds. The travel time standard deviation in these scenarios is increased however from 62.4 second to 86.6. This indicates a more wide average speed distribution than presented before. It can also be seen that the distribution of the cautious CAVs is more skewed toward lower travel times in figure 5.12b. Why this is exactly is shown later this section when the queue forming and speeds are discussed.



(a) Vehicle travel time averages

(b) Vehicle travel time distributions

Figure 5.12: Vehicle travel times and distributions at 0% and 100% CAV penetration with early merge and increased headways enabled

The travel times observed in the normal and all knowing CAVs scenarios are slightly increased as a result of the longer headway that is communicated to the vehicles within the work zone. This effect is only marginal however. Both normal and all knowing CAVs take 388 seconds to clear the network with added communication, where they did this in 383 and 382 seconds without it. Both travel time standard deviations are increased as well to 3.1 and 2.5 seconds. The travel times are thus distributed slightly wider, but this effect is only very small.

Queue length

With the implementation of the early merging and the increased headway just before entering the work zone, the scenarios with cautious CAVs remain the only scenarios where persistent queues form. The average queue length, and the standard deviations of these averages are presented in figure 5.13. When comparing the queues that form over time in the scenarios with communication to those presented in figure 5.3, it can be seen that at lower penetration rates the queues are affected in a positive way. The queue that forms with 25% cautious CAVs with early merge and increased headways enabled are shorter than those that form without. The queues with 50% CAVs on average are of similar length at the end of the simulations, but do not reach this length as early. In the 75% and 100% cautious CAVs scenarios the congestion is much worse than in a situation with no communication. The length of the queues is more than doubled for the 75% scenarios, and the standard deviations are vastly increased as well. The queue length in the 100% scenarios could even be longer than indicated in figure 5.12, but the measurements stop at 2 kilometers ahead of the work zone.

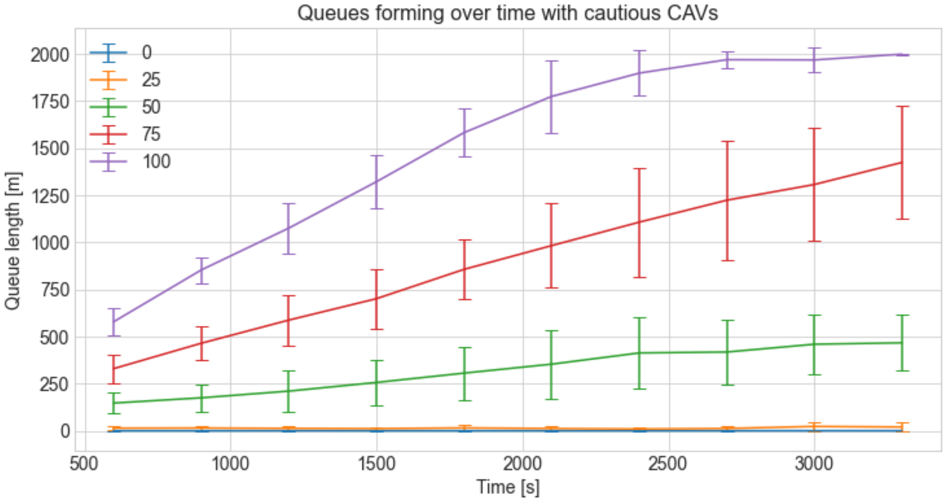
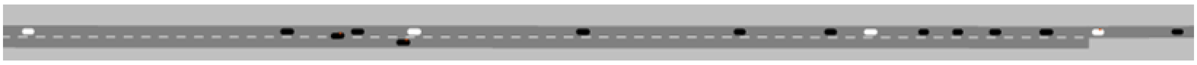
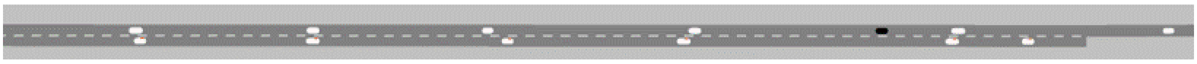


Figure 5.13: Queues forming over time with cautious CAVs with early merge and increased headways enabled

To illustrate why the queues do not form at lower penetration rates, but do form at an extreme rate with higher penetration rates two screenshots of the right lane closure network are presented in figure 5.14. The top figure shows a traffic situation with 25% CAVs, and the bottom situation shows a situation with 75% CAVs. At lower CAV penetration rates, the CAVs are told on time that they have to switch to the right lane. They do this while the CVs remain distributed over both lanes. Because the CVs are able to merge into smaller gaps, they are able to merge later. This causes the CAVs that are following to slow down slightly but traffic continues to flow. With higher penetration rates the CAVs are told to change to the left lane at the same moment as in the other scenarios, but because there are a lot more CAVs in the network the left lane becomes cluttered. This happens relatively fast because these CAVs maintain a longer headway which reduces lane capacity. The CAVs that remain on the right lane want to change lanes as well, but cannot because they require more space to merge as we have seen before. This is still the case, since the CAV behaviour itself did not change. This leads to a situation in which a queue is formed, on the right lane only, with CAVs that are unable to make the lane change. This queue gets longer as time transpires. On the left lane, traffic generally is able to continue to flow because the cautious CAVs are so careful in their decision to change lanes.



(a) 25% cautious CAVs



(b) 75% cautious CAVs

Figure 5.14: Screenshots of VISSIM showing the traffic situation right before the bottleneck with cautious CAVs(white) and CVs(black) at a right lane closure with early merge and increased headway enabled

Speeds

The speed distribution in figure 5.15 shows many of the same characteristics as figure 5.4. There are however also quite some differences. The average speed among all vehicles over all scenarios is increased from 91.2 to 98.1 km/h and the standard deviation is reduced from 22.3 to 17.4 km/h. This indicates that the speed distribution in general is more homogeneous. The improvement is made with the cautious CAVs. Their average speed is increased from 60.2 to 81.0 km/h while maintaining a standard deviation of 32 km/h. The speed distributions of the other vehicle types are altered as a result of the measures as well, but these effects smaller. The 25th percentile is shifted from 93.5 to 98.2 km/h. The group of vehicles below this speed consists almost exclusively of cautious CAVs. The all knowing and normal CAVs are distributed around the speed even more than without communication. The median (50% mark) is shifted from 97.3 to 100.0 km/h and the 75th percentile is shifted from 100.8 to 102.7 km/h. The maximum recorded speeds is found to be 130 km/h.

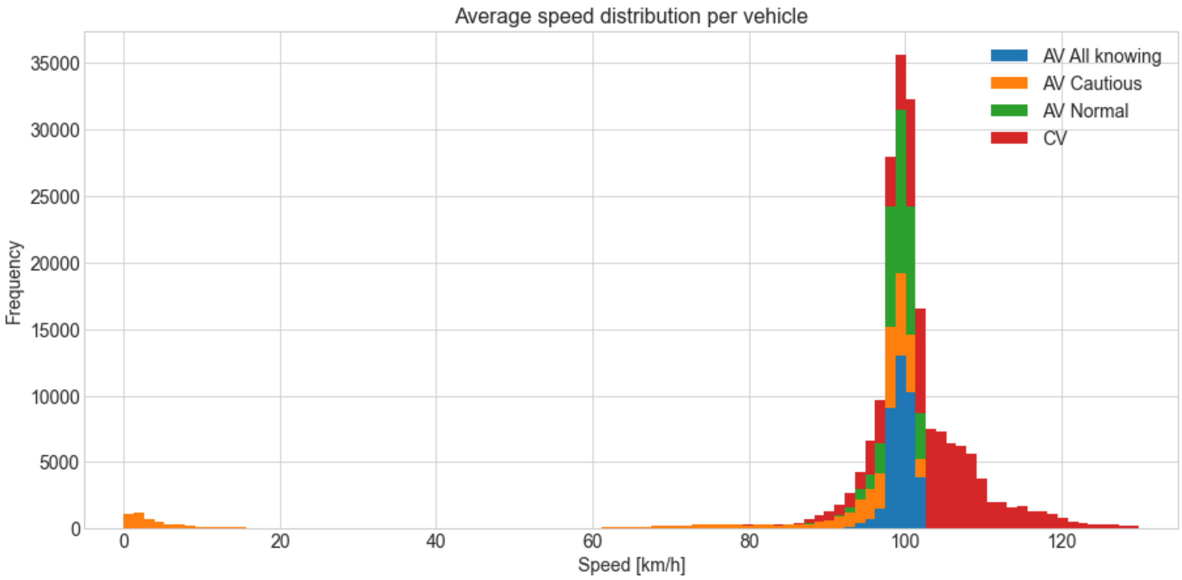
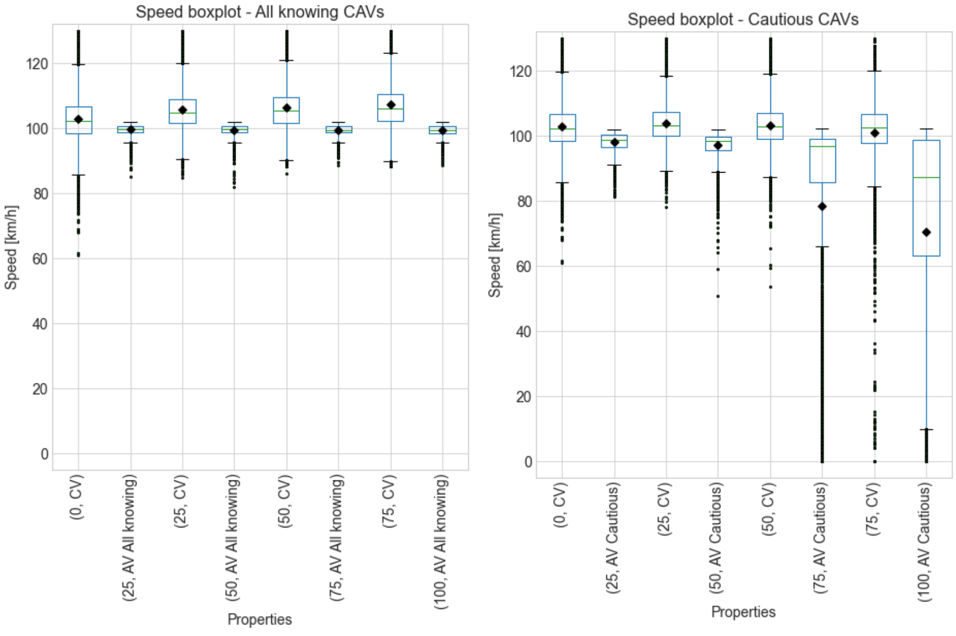


Figure 5.15: Average driving speeds of different vehicle types on the road section right before the right lane closure with early merge and increased headway enabled

The individual speed distributions per CAV scenario are changed as well as a result of the traffic measures. Boxplots of these distributions grouped by vehicle type and penetration rate on the road section right before the right lane closure are presented in figure 5.16. Earlier it was found that the speed distributions of the normal and all knowing CAV scenarios are very similar. Because this is the case with the implementation of the traffic measure as well, here only the results of the all knowing and cautious CAV scenarios are presented. Even more than without communication, the speed distribution of the all knowing CAVs remains the same as the penetration rate increases. With communication enable the amount of lower speed outliers is reduced and the average speed among all knowing CAVs is slightly increased to 100 km/h.



(a) All knowing

(b) Cautious

Figure 5.16: Speed boxplots grouped by vehicle type and penetration rate on the road section right before the right lane closure with early merge and increased headway enabled

What stands out is that the speeds of CVs increase as all knowing CAVs become more prevalent. Without communication the average speeds of CVs remained the same as CAVs increased. In figure 5.16a it can be seen that CV speeds increase slightly, from 102 km/h with no CAVs, to 107 km/h with 75% all knowing CAVs. The amount of low speed outliers is also reduced. This is a result of the reduced number of traffic conflicts such lane changes and overtaking manoeuvres, but also because the slower driving CAVs are centralized on one lane which allows CVs to overtake them.

The biggest effects of the early merge and increased headway measures are visible in figure 5.16b. The speed distributions in this figure are consistent with the forming of queues that is presented in figure 5.13. The average speeds of CVs are almost unaffected by the forming of the queues. The lower speed outliers increase, but the general distribution of CV speeds remain almost the same as cautious CAVs increase in number. This is due to the fact that queues almost exclusively form on the right lane. The traffic measures have a major effect on the speeds of cautious CAVs. Without communication, the average speeds of these vehicles was immediately reduced at 25%, and would only decrease further as this share increased. With communication it can be seen that the average speeds throughout simulations remain relatively constant at 25% and 50% CAVs. At 50% the outliers do increase in number. It is only at 75% and 100% cautious CAVs that the speeds drop significantly. Even these distributions are skewed towards higher speeds, because the CAVs that are able to make the lane change are able to drive a cruising speed. The vehicles that get stuck, are barely able to merge into the right lane which prevents them from completing the network. Because travel times are aggregated per vehicle, this leads to the average speeds to be higher since the same vehicles remain stuck in traffic.

Figure 5.17 presents the general speed distribution of different vehicles over the road section within the right lane closure work zone itself, with early merge and increased headway enabled. The distribution is similar to the situation without these measures, although the average speeds are more centralized around the median of 68.7 km/h. Speeds in general are more homogeneous, but slightly lower. This difference is only very small (0.3 km/h difference). Since the individual distributions per vehicle type and per CAV penetration rate scenario are so similar to the simulations without communication, these additional figure are not presented in this chapter. These figures can be found in Appendix D.

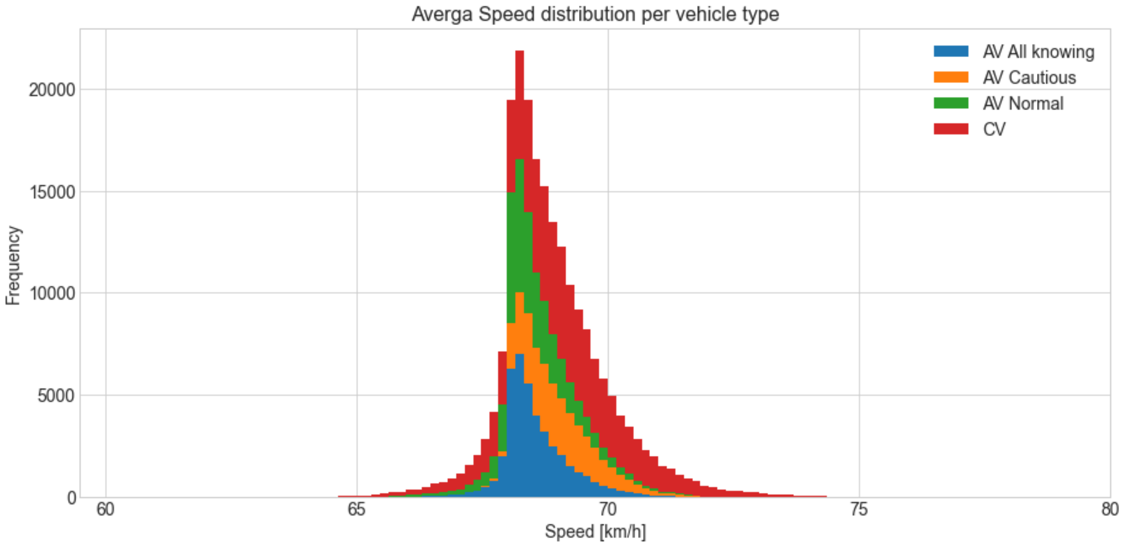


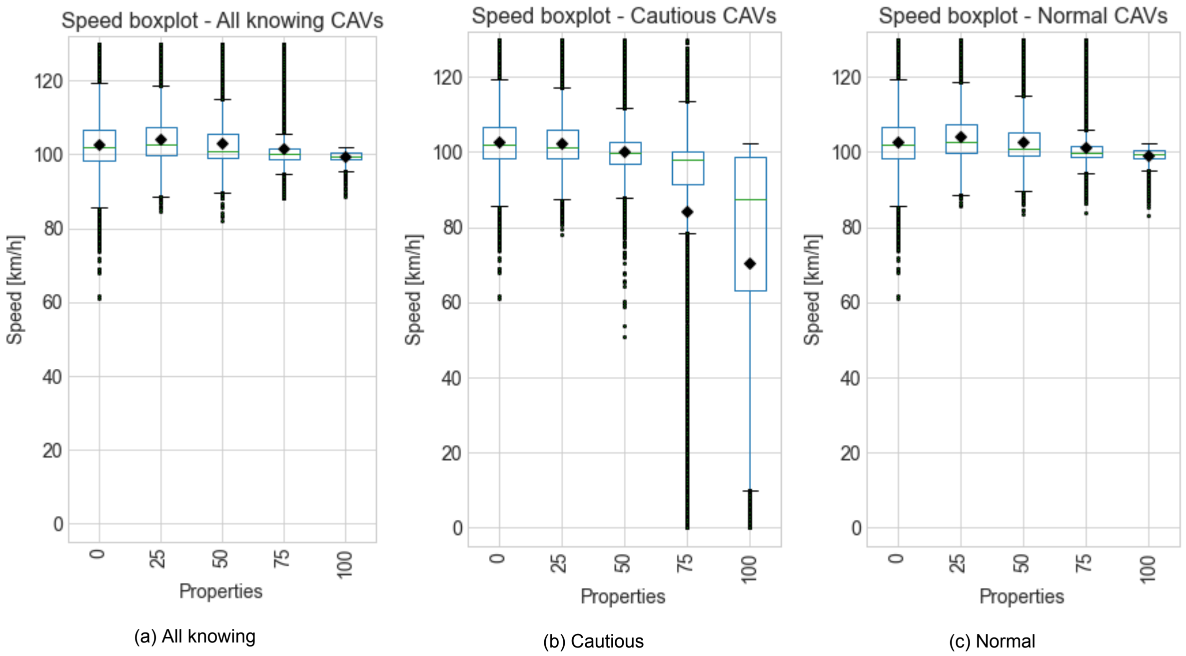
Figure 5.17: Average driving speeds of different vehicle types on the road section within the right lane closure with early merge and increased headway enabled

Traffic safety

Speed variability

In general, the implementation of the communication strategies decreases the speed variability in the simulation scenarios with normal and all knowing CAVs. When comparing the figures in figure 5.18 to those in figure 5.8, the observed speeds are slightly higher, but more homogeneous. There are a lot less outliers and the boxplots itself are more centralized.

At lower penetration rate this effect is the same in the scenarios with cautious CAVs. As long as no congestion forms the speeds are very homogeneous. As mentioned before however, the communication strategy creates problems for the cautious CAVs at higher penetration rates. In these scenarios a lot of congestion occurs, but only on the right lane. The speed differences only become larger and the congestion on the right lane becomes more persistent. The left lane is able to flow freely but this creates very large speeds differences that increases the impact of a potential crash.



(a) All knowing

(b) Cautious

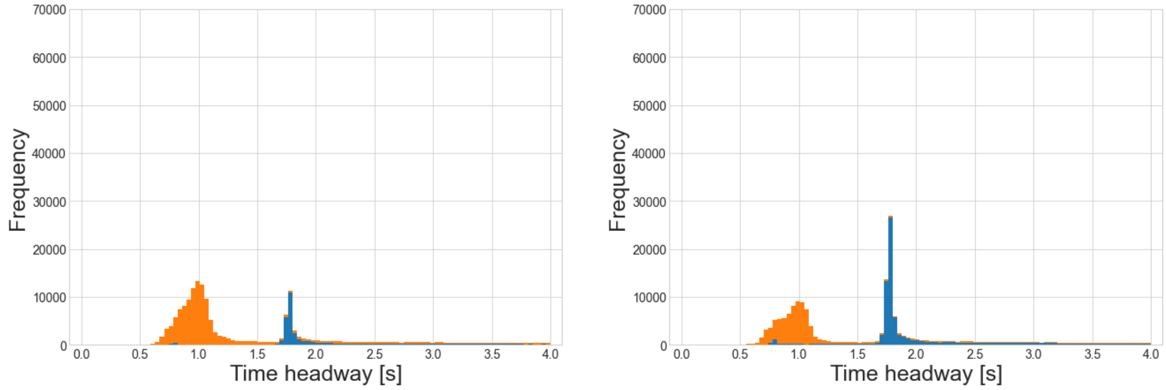
(c) Normal

Figure 5.18: Speed variability boxplots grouped by scenario on the road section right before the right lane closure with early merge and increased headway enabled

Time headways

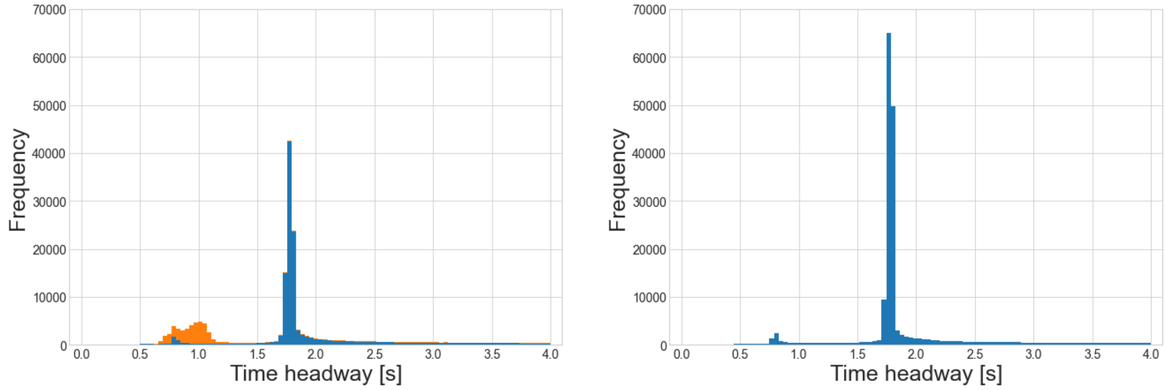
The vehicle headways are mainly affected by the communication measure that tells normal and all knowing CAVs to adapt a longer headway (of 1.5 seconds) 750 meters ahead of the work zone. This measure should make the transition of traffic into the work zone more fluid, and prevent dangerously short headways and hard braking. The communication measure that tells CAVs to merge early has an effect as well however. This measure prevents that CAVs have to merge late, right at the lane reduction, which leads to other vehicles having to brake. The vehicle headways, with their respective driving speeds of all knowing CAVs are presented in figure 5.19. The time headway distribution of the normal CAVs is very similar to this distribution. This distribution can be found in appendix D.

The distributions in figure 5.19 and 5.9 are very similar but the peak is moved from 0.9 to 1.7 seconds. This is a smaller time headway than those observed with cautious CAVs, even though the communicated headway is the same as that of cautious CAVs. This confirms the earlier stated presumption that that time headway of cautious CAVs is longer than the minimum headway as a result of the ”enforce absolute braking distance” feature. Upon closer inspection it can be seen that there is a small second peak at 1.1 seconds. This is a result of the fact that vehicles at first are still driving at their default settings, which use a smaller time headway.



(a) 25% all knowing

(b) 50% all knowing

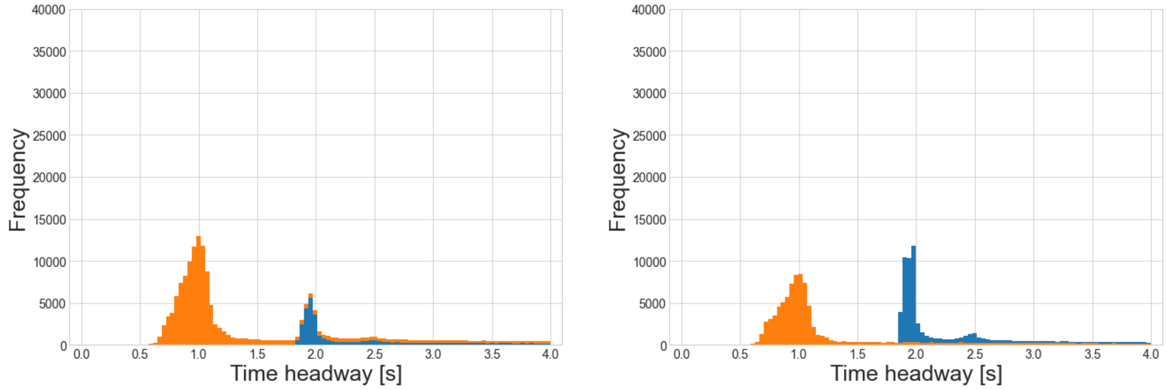


(c) 75% all knowing

(d) 100% all knowing

Figure 5.19: Frequency plot of simulated time headway observations at different penetration rates of all knowing CAVs (blue) in combination with conventional vehicles (orange) with early merge and increased headway enabled

The problem that still remains however is that the CAVs tend to brake quite hard which still leads to the tail that can be seen at the left side of the peak in 5.19d. This leads to a minimum time headway of 0.25. This is the same as the situation without communication. It is clear that vehicles keep a longer headway within the work zone itself. This is consistent with the headways kept by cautious CAVs without communication. This is logical, since cautious CAVs already maintain a default headway of 1.5 seconds. The CVs also benefit of the communication. Because the CAVs transition more gradually from 100 km/h to 70 km/h they can maintain longer headways. CVs keep a headway within the work zone itself that is just as short as observed in the simulations without communication.



(a) 25% cautious

(b) 50% cautious

Figure 5.20: Frequency plot of simulated time headway observations at different penetration rates of cautious CAVs (blue) in combination with conventional vehicles (orange) with early merge and increased headway enabled

The headways of vehicles in the cautious CAV scenarios are presented in figure 5.20. Only the scenarios with 25% and 50% are presented, since the other two scenarios do not provide a feasible traffic situation on which the headways can be assessed. The CAV headways in these figures are generally the same as those in figure 5.10. This is because cautious CAVs already maintain a headway 1.5 seconds by default, so they are unaffected by the headway altering measure. The early merging does have a slight effect on the way in which the headways of cautious CAVs are distributed. The time headways of these CAVs is more spread although this effect is only very slight. There is a no noticeable effect of the early merging on the headways that are maintained by the CVs however.

Lane changes

As a result of the early merging communication to the CAVs the number of lane changes that takes place on the road section before the work zone is heavily influenced. In figure 5.21 it can be seen that the biggest reduction in the number of lane changes happens between 0 and 25%. After this initial reduction, the number of lane changes in the normal and all knowing CAV scenarios remains stable at 1969 and 1887 lane changes respectively. This stabilisation can be explained by the more homogeneous travel speeds that are observed in the simulations. Because speed differences are smaller, vehicles make fewer lane changes to overtake other vehicles. Because all normal and all knowing CAVs shift to the left lane over time, and they stick to the speed limit as well, faster driving CVs have to adjust their speeds and slower driving CVs are overtaken without a lane change being made.

In the cautious CAV scenarios this number reduces further to an average of only 586 lane changes at 100%. This is because the vehicles that are able to make the transition to the left lane do so immediately. This clutters the left lane, which results in many vehicles on the right lane not being able to make the lane change. These vehicles generally remain on the right lane and queue up.

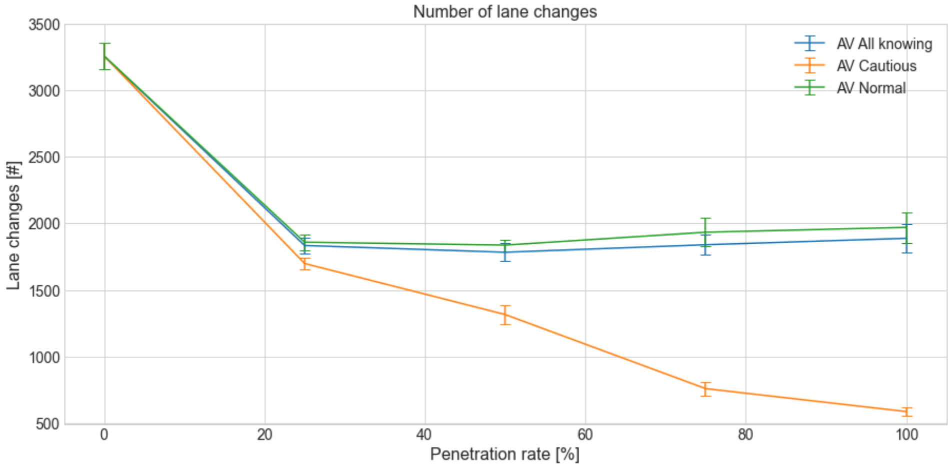


Figure 5.21: Number of lane changes that take place on the road section before the work zone per scenario with early merge and increased headway enabled

Summary

In this section the main effects of the communication measures on the KPIs were assessed. The *early merging* measure was aimed at decreasing congestion in the simulations, especially in the scenarios with cautious CAVs. The *increased headway* measure was aimed at decreasing hard braking before the work zone, and subsequently improving the transition from two to one lanes.

The effects of these two measure on the traffic efficiency are generally positive in simulation. The overall travel times in the scenarios with cautious CAVs were decreased quite severely. The travel times in scenarios with normal and all knowing CAVs were slightly increased as a result of the increased headways right before and inside the work zone. The queues were vastly decreased in scenarios with 25% and 50% cautious CAVs. At higher penetration rates the early merging measure looses its advantages however because the road capacity is reduced too much as a result of the long headways these vehicles maintain. Normal and all knowing CAVs still do not cause any significant queues in front of the work zone with the measures enabled. The measures also have a positive effect on the general speeds, except in those scenarios where significant congestion occurs (50% and 75% cautious CAVs). In all other scenarios traffic is able to drive faster and in a more homogeneous fashion. This means that the speed differences between vehicles are smaller, and that vehicles are able to drive the speeds they want to drive.

The effects of these two measure on the traffic efficiency are generally positive as well. The speed variability is vastly reduced when traffic is able to flow. This makes traffic more safe. In the cases where significant congestion forms, this congestion only forms on the right lane and traffic on the left lane drives at cruising speed. This leads to very large speed differences that are very unsafe. The headways are increased noticeably as a result of the measures. This is a result of the measure that tells CAVs to maintain a longer headway, but also a result of the less turbulent traffic situation as a result of the early lane changes. Furthermore, because vehicles maintain a longer headway, they do not have to brake as hard when a preceding vehicle brakes. This also leads to safer headways. The number of lane changes that are made per scenario are reduced across all scenarios. Because CAVs are told to change lanes early and stick to the left lane, these vehicles only switch once in the last two kilometres before the work zone. Conventional vehicles also change lanes less as a result of this.

5.4. Conclusions

The impact of cautious CAVs on the traffic efficiency without additional communication measures was quite negative. Travel times increased severely, queues increased and speeds dropped as these vehicles increased in share. This can be explained by the large amount of space these vehicles require to change lanes, and the large time headways that they maintain. This severely reduces road capacity and causes issues when a bottleneck is part of the network, such as a right lane closure. The impacts of normal and all knowing CAVs on the traffic efficiency without additional communication measures were found to be fairly neutral. Travel times increased, but only very slightly. This is a direct result of the desired speed distributions that are assumed for these vehicles compared to those of conventional vehicles. No queues formed in scenarios with these two CAV types since they require less space to change lanes and merge cooperatively. The average speeds were slightly reduced as the CAVs increased, but this is again due to the desired speed distributions of the vehicles.

The impact of cautious CAVs on the traffic safety without additional communication measures was very negative as well. Speed variability on the road section before the road work increased severely. This is due to the queues forming only on the right lane, while traffic on the right lane was able to continue driving at cruising speed. When queues formed in a traffic situation with conventional vehicles, the vehicles in the queue started to change lanes which caused the congestion to form on both lanes. However, the cautious CAVs are programmed not to change lanes when this causes risks. This led to a situation in which a queue of cautious CAVs formed on the right lane, while a mix of cautious CAVs and conventional vehicles continued to drive on the left lane. This led to dangerously large speed differences. Cautious CAVs do maintain a safe headway, but do not have an impact on the headways maintained by conventional vehicles. The number of lane changes is reduced severely. This is because the cautious CAVs are not physically able to make the lane changes. The impact of normal and all knowing CAVs on the traffic safety without additional communication measures is more positive. Speed variability is reduced severely and the number of lane changes that take place is reduced as well. The headways that these CAVs maintain are short, but this is one of their key characteristics as formulated by Olstam and Johansson (2018). The effects that this has on the headways maintained by conventional vehicles is minor in simulation. The braking in front of a speed reduction zone does however cause dangerously short headways.

The communication strategies that were implemented, early merge and increased headway, were moderately successful. The early merge, aimed at relieving congestion, was very successful in relieving the congestion that formed at lower penetration rates (25 and 50%) of cautious CAVs. The CAVs changed lanes early, and the conventional vehicles were able to merge later because the cautious

CAVs maintain a long headway and the CVs, as formulated by van Beinum (2018), require little space to merge. At the higher penetration rates (75 and 100%) the effects were the exact opposite however. The CAVs that were able to change lanes immediately did so, but those that were not able to change lanes directly got stuck on the right lane and formed very long queues. This is a logical outcome when considering that the early merging to the left lane takes up all the lane capacity. In the scenarios with normal and all knowing CAVs the early merging led to no additional issues, since these vehicles require less space to merge and change lanes more cooperatively. The increased headway communication, aimed at making the transition into lower speed areas more smooth, was relatively successful. On average this measure reduced the number of observations in which a short headway was maintained at a high speed, for both the CAVs and the CVs. There are however still a large number of normal and all knowing CAVs that do maintain a very short headway in the transition areas. In general the communication strategies work as intended and have the results that would be expected.

6

Reflection

Before the results can be assumed to be correct for answering the research questions, the model outcomes are compared to literature as part of the reflection. In this step, the check is made whether the model sufficiently represents the real-life situation. In the case of this research, this real-life situation is only hypothetical since connected and automated vehicles are not implemented on a large scale in practice yet. Models that represent a real-life situation are generally validated by comparing the results with measurement data from the field. However, since this study models a hypothetical future situation this is not a possibility. Therefore a reflection is carried out by comparing the model output to the output of studies that conduct similar simulations with CAVs in mixed traffic. Not all studies look at the same KPIs and values however, so multiple studies are used. The studies that are used for validation of traffic efficiency aspects are van der Tuin et al. (2020b), Berrazouane et al. (2019), Aria (2016) and Rios-Torres and Malikopoulos (2017). Traffic safety aspects are validated based on van der Tuin et al. (2020b), Morando et al. (2017, 2018) and Papadoulis et al. (2019).

6.1. KPI face validation

The simulations show that different CAV types have different effects on the travel times. Cautious CAVs increase the travel times significantly, and normal and all knowing CAVs increase the travel time only slightly. These results are in line with the results of van der Tuin et al. (2020b), Berrazouane et al. (2019) and Rios-Torres and Malikopoulos (2017). Van der Tuin used the three different CAV types, in combination with the calibrated conventional vehicles (van Beinum, 2018) in a network with weaving sections. What showed there, is that cautious CAVs increased the travel times over the network with more than 300%. Normal and all knowing CAVs actually decreased the travel times slightly in their research. Rios-Torres and Malikopoulos (2017) found a slightly higher traffic flow in a scenario with 0% CAVs than in a scenario with 100% CAV, and explained this with the given that conventional vehicles drive over the speed limit where CAVs do not. Berrazouane et al. (2019) also observed a slight increase in travel times due to increased headways and more homogeneous speed distributions. These results are consistent with our travel time results.

The queues that form in the simulations are in line with the results shown by van der Tuin et al. (2020b). In their simulations cautious CAVs experienced great difficulties with merging onto the motorway which led to a situation in which no more vehicles were able to enter the network as a result of congestion. In this study cautious CAVs also have problems with merging and large queues form in front of the work zone. The other studies used different formulations for their CAVs, so these are less comparable.

The speeds that are observed with increasing shares of CAVs also line up with earlier research. On this study it was found that the average speeds slightly drop, but that the distribution become much more homogeneous as CAVs increase in number. The speed distributions that are used in this research are the same as those used by (van der Tuin et al., 2020b), since they are both based on Olstam and Johansson (2018) and Sunkennik et al. (2018). Van der Tuin does not use speed as an output, but it is stated that the observed speeds are much more homogeneous. Aria (2016) also concludes that

CAVs do not drive over the speed limit, and that the speeds differ less from each other. This is also in line with our results. Berrazouane et al. (2019) and Rios-Torres and Malikopoulos (2017) make no conclusions in relation with speed.

In the literature, the effects that CAVs have on the safety are mainly assessed in the general sense by looking at the number of conflicts. What is found in relation to the KPIs used in this study, is that CAVs generally maintain a shorter headway than conventional vehicles (Papadoulis et al., 2019). This is a finding that was made in this study as well. Additionally, van der Tuin et al. (2020b) found that the calibrated CV behaviour tends to take high risks when merging. This is an observation that is made in this study as well. Morando et al. (2017) finds that the number of conflicts in traffic is vastly reduced. This can be related to the number of lane changes that are observed in the simulations in this study. The number of lane changes are vastly reduced as CAVs increase. Therefore this finding is consistent with literature as well.

Overall the KPI outcomes are found to be consistent with earlier research, and those that slightly differ can be explained based on a difference in simulation approach. It can therefore be concluded that the simulation set-up in essence is valid. This does not necessarily mean that all outcomes are fully correct. It means that the base behavioural aspects and interactions between vehicles are consistent with the theories, and that the outcomes that follow as a result of this are logical. It therefore is valid to experiment with communication strategies to see what the resulting effects are on the traffic performance.

7

Discussion

The goals of this study were to better understand the impacts CAVs will have on the traffic efficiency and traffic safety in highway work zones under different circumstances, and to be able to make a well formulated estimation on how current communication in work zones will change in the future. Because research into the future developments and impacts of automated vehicles is still constantly changing, interpreting results bluntly is an ever glooming danger. As is the case with all studies focusing on connected and automated driving, this study too is based on many choices and assumptions. In interpreting results, it is important to know these choices and assumptions, and to know what this means for the robustness of the results. Is this chapter the choices and assumptions made in this study are discussed and reflected upon critically. By doing so, limitations can be identified and the results can be interpreted better with these limitations in mind. The following subjects are discussed in this section: the simulated networks, the simulated driving behaviours and the simulated communication strategies.

7.1. Simulated networks

In the literature review many factors were identified that impact the capabilities of CAVs to read the road ahead of them. These include factors such as consistent road markings, consistent road signs and not too many signs in close succession. These are already three phenomena that are in practice inherently linked to road works and work zones. In order to be able to assess the impacts of CAVs on the traffic efficiency and traffic safety on a microscopic level, the major assumption was made that CAVs are able to drive through work zones if we design them in a suitable way. Although this assumption is not unrealistic in the long run, there are many changes necessary to the way in which we design our work zones for this assumption to become reality. The way in which this might alter the work zone design will also alter the observed traffic performance in general. This is however out of scope for this study. The interactions between individual infrastructural aspects and connected and automated vehicles should be further studies in future work.

The work zone design of the 3-1 contraflow system was, among other reasons, chosen to assess how CAVs and CVs would behave on the road section that contains curves and has a reduced lane width. The literature points out that especially CAVs struggle to steer through s-curves at high speeds (García et al., 2020, Reddy, 2019), and that CAVs and many human drivers change their behaviour as a result of a reduced lane width (García and Camacho-Torregrosa, 2020). It was found however that the effects of these curves and reduced lane width areas can not be captured with VISSIM simulation. This could lead to a deviation in results to those that would be found in a field operational test. It is found to be impossible to assess these interactions in a simulation test. In future work focusing on the capabilities of CAVs in these environment, more practical methods should therefore be used to assess these effects.

The results of the 3-1 contraflow system show that the behaviour within this network is very similar to the behaviour shown in the right lane closure. In the simulations, the network contains one origin and one destination. Vehicles travel between these two points over one road that splits up and is joined together again. This means that vehicles do not have to choose one of the two directions at the separation in order to reach a specific destination. In reality, 3-1 contraflow systems are mostly implemented on sections of road where there is an on- and/or off-ramp that is essential for traffic in the area. This is not the case in the simulated network. This also has an impact on the results. As stated, the results of the 3-1 contraflow system do not show any congestion. This is because vehicles do not have to make a choice between the two directions and can continue driving on the lane they are already driving on. If they would have to make a choice, by having another destination halfway through the system, the cautious CAVs as formulated in the simulations would probably experience issues with changing lanes. They have issues with this in the right lane closure as well, so here the same would be expected. For the other vehicle types this is not necessarily the case, but it is an elaboration that is worth considering nonetheless. This missing feature in the network makes the results of the 3-1 contraflow system more similar to the results of the right lane closure. These additions to the network should be added in future expansions of this work.

7.2. Simulated vehicle behaviour

Three distinct parameter sets were formulated based on Olstam and Johansson (2018) to simulate CAV behaviour. These sets included 25 individual parameters and changes to the distributions. From literature we know that not all parameters have the same impact on the shown behaviour in simulation. However, based on the simulations that were executed it is very difficult to draw conclusions regarding individual vehicle parameters. About some individual parameters (headway, lane changing behaviour, speed distributions, enforcement of absolute braking distance) a better idea is obtained as to what their impact is on the driving behaviour as a whole. Most of the individual parameters are still very uncertain.

For instance, it is known that the vehicle headway has major implications for the driving behaviour, but for traffic in general as well. It determines how easily vehicles can change lanes and how fast a vehicle has to react to the braking of a preceding vehicle. But it is also of influence on the general road capacity, the amount of congestion that forms on the road and the travel time gains that are made. Seeing that the calibrated driving behaviour by van Beinum (2018) maintains a significantly shorter headway than the VISSIM default (calibrated: 0.5 seconds, default: 0.9s), this has significant influence on the results.

Another parameter that is very influential on the travel time gains that are made as CAVs increase in share, are the desired speed distributions. These distribution functions are particularly important, as they have an impact on link capacity and achievable travel times (PTV Group, 2019). The distributions are shaped by a probability density function (PDF) around the legal speed limit. Even though the default PDFs are based on empirical data, the shapes for CVs vary a lot per speed limit. The distribution of 120 km/h prescribes that 51% of traffic wants to drive over the speed limit and a maximum speed of 155 km/h. The distribution of 100 km/h prescribes that 90% of traffic wants to drive over the speed limit and a maximum speed of 140 km/h. Seeing that the PDFs of CAVs are always linearly distributed around the speed limit +/- 2, this has major implications for the possible travel time gains. Implementing CAVs in a 100 km/h network shows less travel time gains (or more losses) than implementing them in the same network with a 120 km/h speed limit. This holds for other speed distributions as well. The assumption that CAVs will stick to the speed limit in itself is a large assumption. One can argue that the vehicle owner will set a speed for the CAV and let it drive on its own from there on. This has implications for the speed distributions and the potential travel time gains.

Additionally, the lane changing behaviour and the tolerances that come with this behaviour are of impact for the results. In visual observations made of the simulations it was observed that the calibrated CVs sometimes take large risks with merging at the last moment. Cases were observed wherein calibrated CVs would merge while only maintaining a headway of 1.5 meters at speeds of 90 km/h. Although this does happen sporadically in reality, this seems undesirable in simulation and could be prevented with different driving behaviour. Altering the lane changing behaviour of CVs would also change the potential gains as a result of CAVs. Hypothetically, these can tolerate higher risks since they can react to sudden speed changes in real-time without an added reaction time. This would allow them to move through traffic more smoothly which would increase the gains.

As is clear, the way in which CVs are formulated is highly influential on the results. The travel time results that were found in this study were consistent with the findings made by van der Tuin et al. (2020b) in the simulations where calibrated CV driving behaviour was used. In additional tests that were done in that research where the VISSIM default driving behaviour was used for CVs, the travel time gains as a result of a larger share of CAVs was larger. This is also due to the headways that are maintained. The headways that are maintained by the calibrated cars of van Beinum (2018) are quite short, since these were calibrated for the Dutch road network with large traffic intensities (and possibly congestion). Although this is the traffic situation that it modelled in this study, this is still something that should be kept in mind when interpreting the results.

These different behaviours would in reality influence each other as well. One would expect that different CAV types would have different effects on the behaviour of CVs. These secondary interaction effects between driving behaviours are not a part of VISSIM however. A conventional vehicle will always want to drive at its own desired speed, even if surrounding traffic is driving at a slower pace. This is clearly visible in the distributions of CV speeds and headways. These are mostly the same among the CAV scenarios, except for those where real congestion form that disturbs the traffic flow. These interaction effects should be a point of interest in future simulation studies.

A factor that would also be dependent on the behaviour of the vehicles, is the road capacity itself. In the simulations the vehicle inputs are simulated through static inputs based on the capacity values as presented by Henkens et al. (2015). These vehicle inputs are meant to simulate a F/C-ratio of 1.0, corrected for the assumption that there are no trucks in the network. These reported capacities are based on a normal traffic situation conform the traffic guidelines. However, seeing that different vehicles are simulated, that behave differently, the road capacity is actually different for all scenarios. Generally, the road capacity increases as normal and all knowing CAVs increase, and decreases as cautious CAVs increase. Computing the actual capacities of all individual scenarios would be possible, but requires too much time to do within the limited time of this study. Therefore it was decided to stick with a non-changing static vehicle input instead of constantly altering the inputs as the vehicle composition change.

Overall it is very important to know what the effects of individual behavioural aspects of CAVs are in simulation. As simulation is an often used method to make estimations of the potential effects that these vehicles will have, these effects should be known better. The current formulation of cautious CAVs is infeasible to implement in traffic in real-life, because it has too many negative effects on traffic efficiency. Normal and all knowing CAVs are very similar in their output, but this does depend on how CVs are modelled in the simulations. In giving advice on the feasibility of CAVs in general, this is something that has to be realized.

7.3. Simulated communication strategies

As was show in the results, the early merge communication strategy works to relieve the congestion that forms at lower penetration rates of cautious CAVs. It is hard however to extrapolate this finding toward situations with different driving behaviour. If CVs would be simulated with more cautious behaviour it is more than likely that the early merging of CAVs would lead to the CVs having trouble merging. This is not the case with the current CVs. However, some literature states that the earliest iterations of CAVs will maintain longer headways than human drivers to ensure safety (Berrazouane et al., 2019, Rios-Torres and Malikopoulos, 2017). This makes the case that such an early merging strategy could be feasible. This communication strategy can be tested with more distributed communication, and more different vehicles setting in order to test the robustness of such a strategy.

The adopting of an increased headway for CAVs in the final road section before the work zone showed to be a moderate success in the simulations. This communication strategy made the transition into the work zone more smooth in terms of speeds and headways than was observed without communication. In the simulations, CVs coped with the braking of CAVs fairly well which shows in the results. Headways are slightly longer and traffic flow is increased because vehicles brake less hard. This is however very dependent on the traffic compositions and vehicle behaviours in general. Also, some of the CAVs still tend to brake quite hard initially which leads to some vehicles still having a very short headway. To improve this communication strategy, and to test its feasibility better, the strategy should be combined with other behavioural changes. These can include changes to the maximum allowed braking settings and to the maximum acceleration. This changes the behaviour of the CAVs slightly, which can improve safety further.

8

Conclusions and recommendations

This chapter presents and discusses the most important conclusions and recommendations that follow from this research. Section 8.1 presents the findings and conclusions to answer to the research questions that were formulated at the beginning of this research. Section 8.2 discusses how these answers enrich the scientific knowledge and how it (partly) fills the gap that was found in the literature. Section 8.3 presents what can be done to use the conclusions in practice. Section 8.4 presents a set of recommendations for future research to be conducted.

8.1. Findings and conclusions

This study looked at the impact of CAVs on traffic efficiency and safety in different work zones in order to formulate feasible communication strategies that were subsequently tested and evaluated. This way work zones can in the future be designed to better suit the traffic properties. The aim of this research was divided into two main goals. These goals were:

1. To better understand the impacts of CAVs on the traffic efficiency and traffic safety in highway roadwork zones in different scenarios.
2. To make a well formulated estimation of how current communication in work zones will need to be changed in the future.

To achieve these goals, a main research question was developed. This main research question was formulated as:

What are the effects of Connected and Automated Vehicles on the traffic efficiency and traffic safety in highway work zones in the Netherlands?

This main research question was then further divided into four sub-questions. These four sub-questions are answered in the following paragraphs. By answering these four sub-questions, one total answer to the main research question is found as well.

What are the effects of different CAV driving behaviour on traffic efficiency and traffic safety in current highway work zone configurations?

In order to find an answer to the first research question, first the driving behaviour of the CAVs was determined. Three types of behaviour were found in literature that were designed to represent different stages of vehicle automation. These are the *cautious* driving logic, the *normal* driving logic and the *all knowing* driving logic. The *cautious* driving logic is formulated in such a way, that the vehicle is never responsible for an accident. This does not mean that they are never involved in an accident, but they are never the one at fault. The *normal* driving logic is formulated to emulate human driving behaviour with the added capacity of measuring distances and speeds of other vehicles via sensors. These vehicles take more risks, but these risks are calculated. The *all knowing* driving logic is formulated to be the ”perfect” CAV. The vehicle is fully aware of all its surroundings and uses this knowledge to have the best possible performances within the bounds of safety. Two work zone networks were selected based on literature and the outcomes of a workshop with traffic managers of VolkerWessels. The two work zones that were selected are a *right lane closure* and a *3-1 contraflow system*. These choices are at the basis of the simulations built in the PTV VISSIM modelling tool.

The modelling of four scenarios with only one type of vehicle (0% CAVs, 100% cautious CAVs, 100% normal CAVs and 100% all knowing CAVs) was conducted to assess the effects of the individual CAV driving logics alone. The 0% CAVs scenario was used as a benchmark. The traffic efficiency related findings show that conventional vehicles generally perform better than the CAVs. Travel times were the lowest, although the differences with normal and all knowing CAVs were only very small (< 3%). This can by explained by the modelling assumption that CAVs stick to the speed limit, where human driver often drive faster than the speed limit. The cautious CAVs showed a vast increase of the travel times in the right lane closure network. This is a result of the large queues that formed on the right lane in front of the work zone in this network. Because cautious CAVs do not want to take risks they were unable to execute a lane change in busy traffic. This led to a traffic situation in which the right lane was congested, while vehicles on the right lane continued to drive a cruising speeds. The 3-1 contraflow simulations did not show any congestion for any of the scenarios, so no large travel time differences occurred here.

The traffic safety related findings showed that normal and all knowing CAVs increase safety the most. Speed variability was observed to be the lowest with these two vehicle types. This is a logical result of the aforementioned assumption of these vehicle sticking to the speed limit. The number of lane changes was also reduced significantly. The headways maintained by these two CAV types were shorter, but it could be argued that this would not be a problem for CAVs with large technical capabilities. Cautious CAV performed well when looking only at the maintained headways and the number of lane changes, but the speed variability was very large in this scenario. This was again a result of the congestion that formed on the right lane. Traffic on the left lane was able to continue driving at cruising speed, because of the settings of these vehicles. This leads to speed a difference between the two lanes of up to 90 km/h. In reality these speed differences would be considered to be very dangerous.

What are the effects of CAV penetration rates on traffic efficiency and traffic safety in current highway work zone configurations?

For answering the second research question, the penetration rates of the three CAV types were varied from 0% to 100% in four steps of 25%. This led to an additional 9 simulated scenarios per network in which conventional vehicles and CAVs interact with each other.

The effects of the CAV penetration rates on traffic efficiency showed to be fairly linear. As normal and all knowing CAVs increased in share, the speeds and travel times of conventional vehicles and CAVs individually remained the same. For the traffic fleet as a whole the travel times slightly increased and the average speeds decreased, but this was a direct result of the vehicle shares. Interaction effects between the vehicle types was not deemed noticeable in these scenarios. Conventional vehicles did not alter their driving speeds to the CAVs in the areas where overtaking was a possibility. In the work zones themselves these speeds were altered, since overtaking was not possible. The problems that were present with 100% cautious CAVs were found to be a function of the penetration rates as well. At a 25% penetration rate the congestion that forms is very marginal. But as the CAVs become more prevalent, the congestion keeps increasing. With 100% CAVs it was even found that the congestion increases linearly with time when the vehicle inputs remain constant.

The safety related findings showed that the CAV penetration rate is linked to the effects on safety. As normal and all knowing CAVs increased in share, safety improved generally. The speed distributions of the traffic fleet became more homogeneous and fewer lane changes were made. The one factor that was influenced negatively with normal and all knowing CAVs, was headway. In the right lane closure scenarios, it was observed that vehicles showed a dangerously short headway in the transition area in front of the work zone. The general distribution of the headways remained the same as CAVs increased, but these outliers showed relatively more often. The penetration rate of cautious CAVs also affected the safety quite linearly, but then in the negative sense. With more cautious CAVs the congestion showed to get worse and speed variability increased. The headways maintained at high speeds remained unaffected by this. These showed the same distribution for all penetration rate scenarios.

What are promising communication strategies to increase traffic efficiency and traffic safety in highway work zones with CAVs in combination conventional traffic?

Two communication strategies were formulated to relieve observed negative effects of the CAVs. The first communication strategy was an early merging communication strategy that was aimed at relieving the congestion that forms in scenarios with cautious CAVs. 2 kilometers ahead of the work zone, the CAVs were told that they were required to switch to the left lane when they can. They did not have to do this immediately. This measure was proposed earlier in numerous studies and implemented by van der Tuin et al. (2020b). They applied this communication strategy exclusively for all knowing CAVs to pass a moving maintenance vehicle, while not communicating anything to conventional vehicles. This led to issues for conventional vehicles. In our simulations the communication strategy is added as an extra form of communication on top of the conventional communicational measures such as signs. This was estimated to be sufficient information for the conventional vehicles to be able to change lanes on time and not to cause congestion.

The second communication strategy that was identified was a signal that tells the CAVs to adapt a longer headway than normal on the road section ranging from 500 meter ahead of the work zone until the end of the work zone. This new headway was chosen to be 1.5 seconds, which is the default headway for cautious CAVs, since this headway showed a smooth transition into the work zone. The goal of this communication strategy was to prevent vehicles from maintaining a dangerously short headway in the transition area into the work zone, and to increase traffic safety within the work zone itself.

What are the effects of these communication strategies with different CAV driving behaviour, at different penetration rates in different highway work zone configurations on traffic efficiency and traffic safety?

The communication strategies showed to be moderately effective. The early merge communication strategy resulted in a lot less congestion forming at 25% and 50% cautious CAV penetration rates. Conventional vehicles were still able to merge in time which meant that no persistent congestion was formed in these scenarios. At 75% and 100% cautious CAVs the communication strategy lost its benefits. This make sense however, seeing that the road capacity is vastly reduced if all vehicles have to drive on one single lane. This resulted in extreme queue forming. This also improved safety in the scenarios where congestion was relieved, since the large speed differences no longer appeared.

The adoption of longer headways before entering the work zone resulted in a smoother transition into the work zone in terms of speeds. The effect on the headways was twofold however. For some vehicles that were following another vehicle closely, the assignment to increase their headway resulted in hard braking which in turn still led to short headways. Within the work zone itself the longer headways did result in a more constant speed distribution.

8.2. Scientific contributions

The first scientific contribution of this study is that different levels of vehicle automation are simulated within a work zone environment. As mentioned before, work zones are a high risk traffic environment in which automated vehicles are expected to experience difficulties. Because there are still many uncertainties regarding the level of automation that will be necessary for CAVs to become more common practice, it is important to see what the impact is of the level of automation on the performance in these high risk zones. A first step has been made with this research to provide clarity in this field.

The new insights that were obtained showed that if CAVs are programmed to be too conservative, this will lead to major traffic efficiency drops in work zones. This leads to large travel times, but could potentially also lead to dangerous situations as a result of large speed differences if conventional human drivers are a part of the traffic fleet still. The extent to which this happens is however very dependent on the driving behaviour of conventional vehicles as well.

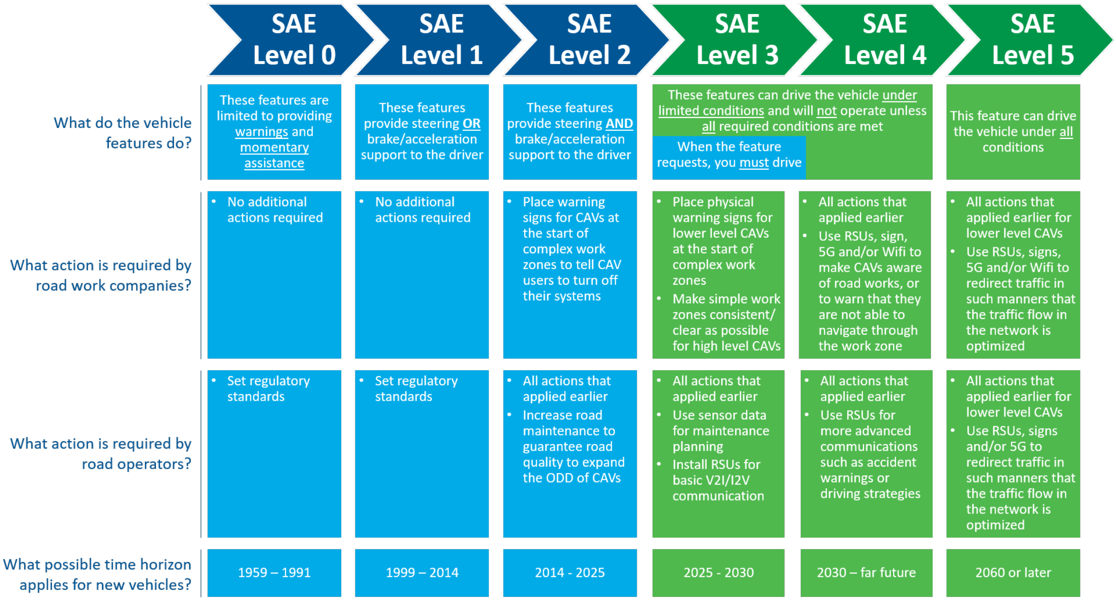
Additionally, the insights showed that CAVs with more aggressive behaviour, such as the all knowing CAVs, could lead to safety issues for conventional drivers since these vehicles take risks that would in reality not be possible. Simulations do not simulate accidents, but it is very likely that these would occur because of interactions between aggressive CAVs and conventional drivers.

The second scientific contribution is the successful implementation of an early merging strategy, in combination with the adoption of an increased headway for aggressive CAVs to increase traffic efficiency and safety in work zones. In previous studies the early merging strategy was implemented as a replacement of the conventional means of communication(road signs etc.). This led to traffic situations where conventional human drivers would perform worse. In this study this measure was implemented as an addition to the conventional means of communication which resulted in an increase in traffic efficiency and safety. These results are not directly suited for extrapolation toward real-life traffic situations however. The robustness of this measure should first be tested extensively with other traffic compositions and driving behaviours before physical tests can be applied.

The communication of a longer headway to relatively aggressive CAVs showed potential to increase safety, although increasing the headway alone is likely not enough to ensure safe interactions with conventional traffic. These more aggressive CAVs still tend to accelerate/decelerate harder than usual which could in reality lead to problems. These are not visible directly within the simulations, but would likely occur in real-life.

8.3. Practical applications

The practical applications of this research are graphically represented in figure 8.1. The SAE J3016 levels are used as a basis for this figure. The time horizons indicate at what time the automation level will make its entry in new vehicles, and are only an estimation. They should not be interpreted literally. This research is commissioned by VolkerWessels. Therefore the first part of the practical applications focuses on the applications for road work companies. The second part presents the practical applications for road operators.



	SAE Level 0	SAE Level 1	SAE Level 2	SAE Level 3	SAE Level 4	SAE Level 5
What do the vehicle features do?	These features are limited to providing warnings and momentary assistance	These features provide steering **OR** brake/acceleration support to the driver	These features provide steering **AND** brake/acceleration support to the driver	These features can drive the vehicle under limited conditions and will not operate unless all required conditions are met When the feature requests, you must drive		This feature can drive the vehicle under all conditions
What action is required by road work companies?	• No additional actions required	• No additional actions required	• Place warning signs for CAVs at the start of complex work zones to tell CAV users to turn off their systems	• Place physical warning signs for lower level CAVs at the start of complex work zones • Make simple work zones consistent/ clear as possible for high level CAVs	• All actions that applied earlier • Use RSUs, sign, 5G and/or Wifi to make CAVs aware of road works, or to warn that they are not able to navigate through the work zone	• All actions that applied earlier for lower level CAVs • Use RSUs, signs, 5G and/or Wifi to redirect traffic in such manners that the traffic flow in the network is optimized
What action is required by road operators?	• Set regulatory standards	• Set regulatory standards	• All actions that applied earlier • Increase road maintenance to guarantee road quality to expand the ODD of CAVs	• All actions that applied earlier • Use sensor data for maintenance planning • Install RSUs for basic V2I/I2V communication	• All actions that applied earlier • Use RSUs for more advanced communications such as accident warnings or driving strategies	• All actions that applied earlier for lower level CAVs • Use RSUs, signs and/or 5G to redirect traffic in such manners that the traffic flow in the network is optimized
What possible time horizon applies for new vehicles?	1959 – 1991	1999 – 2014	2014 - 2025	2025 - 2030	2030 – far future	2060 or later

Figure 8.1: Timeline of action that should be considered by road work companies and road operators at different automations levels (Adated from SAE J3016 (SAE International, 2018), time horizons based on (Smarttransport, 2020, Smith et al., 2017, van Asselt, 2019))

Applications for road work companies

Figure 8.2: Prohibition sign

As figure 8.1 shows, road work companies were not required to act proactively in the last decades. This way of working will initially not have to change drastically. Current new vehicles are equipped with level 2 vehicle automation systems, although the number of vehicles that has this technology is still limited. These vehicles still rely on sensors while driving that can have issues reading the roads within complex road work zones. The first actions by road work companies should not be aimed at making it possible for these vehicles to drive through the work zones, but should warn the vehicle owners that their vehicle is not able to drive through the current work zones. This can be achieved by placing prohibition sign such as figure 8.2 or other warning signs telling drivers they are obliged to take control. When CAVs reach level 3, actions should be taken to make it possible for CAVs to drive through simple work zones safely. This can be done by designing these simple work zones with capabilities of CAVs in mind. Aspects that are of essential importance for the correct functioning of these CAVs are the visibility, consistency and quality of the road, road markings, traffic signs etc. Appendix B presents a full list of physical and digital infrastructure elements that aid the efficient and safe movement of CAVs through work zones. For lower levels of CAVs physical infrastructure elements are more important than digital elements. Digital elements such as a digital map, GPS and traffic management can however already be utilized to increase information both CAVs and CVs can use. In complex work zones, where the road design cannot suit the need of CAVs, signs such as figure 8.2 should still be installed.

As CAVs become more advanced, the capabilities of lower level CAVs should still be kept in mind, since these will still operational. New use can be made of smart infrastructure that will likely become more common by this time, such as road side units (RSUs), 5G (or newer versions), or Wifi. For level 4 CAVs this communication can be used to communicate information to make it possible for the vehicle to move safely through the work zone, or to make them aware that the work zone is still too complex. For level 5 CAVs, the communication can be used exclusively to optimize traffic efficiency and safety.

It is currently too early for road work companies to implement large scale communication strategies aimed at CAVs since the CAV fleet is simply too small. Connectivity in vehicles is a development that transcends automated driving however. Communication strategies aimed at conventional vehicles could be effective as well when the infrastructure and the vehicles are able to communicate. More research into these strategies is required however. Road work companies should be aware of the potential future developments that are possible as CAVs increase in number. If these vehicles are designed to be very cautious, communication can lead to the relieving of congestion and to the increasing of safety. More research into these fields is required however, before investments are made.

Applications for road operators

Regarding automation, road operators used to be mainly concerned with setting regulatory standards to new systems in vehicles. Although this will remain very relevant in the future, other action should be considered as well. Now that level 2 automation systems become more prevalent, road maintenance should be fitted to the system capabilities, since their systems solely rely on sensors that read markings and signs. This way the ODD of CAVs can be expanded which allows for faster advancements in these systems. This includes ensuring the aforementioned visibility, consistency and quality of the road, road markings, traffic signs etc. It also includes considering the effects of road curvature and lane width on the functioning of CAVs (García and Camacho-Torregrosa, 2020, García et al., 2020). The sensors in CAVs can also be used as an opportunity however. The sensor data could potentially be used by road operators to obtain a real-time image of the state of the road markings and signs. This could be used to optimize road maintenance.

In order to be ready when the need arises, road authorities should consider if it is time to begin installing road side units (RSUs) that can be used for digital communication to connected vehicles. This will likely become relevant with the larger scale introduction of level 3 CAVs. Connectivity in vehicles is a development that transcends automated driving as well however. For conventional human driven vehicles RSUs are a good addition that can be used to provide road users with real time information, but for the future of connected and automated driving it will most likely become an essential part of the digital infrastructure. These RSU can be used to warn oncoming traffic, to redirect traffic or to make optimal use of the traffic network by optimizing vehicle routes. This study showed two possible applications of RSUs, namely early merge and increase headway communication, but numerous other applications could be devised.

Generally road operators should take connected and automated vehicles into account in forming their infrastructure policy. In order to facilitate a transition toward automated driving the role of infrastructure is very important. This should be reflected in the policies that are formed. Currently this is not yet the case, but there are studies taking place, commissioned by the dutch government to see how their role might change in the future.

8.4. Scientific recommendations

This research provides rough insights into the effects that Connected and Automated Vehicles will have on traffic efficiency and safety in the future. This is still mostly an explorative study however since it is a quickly developing field of research. The downside of such exploitative studies often is that they often lack finality and that additional studies must be conducted to generate validity and more specific insights. It is therefore important to research many parts of this study more in detail. In this section, a set of possible future research is presented for the scientific field to focus on. This set consists of the following subjects:

- **Simulate different networks**: It was already stated that extrapolating the findings of this study to other networks should not be done bluntly. Therefore it is advised to test the findings of this study in different work zone networks, that contain a more dynamic traffic situation. This can be done by adding on- and off-ramps, increasing the number of lanes or by simulating other typical road work configurations as formulated by CROW (2020).
- **Study additional communication strategies**: The communication strategies in this study were determined based on the first observations of the simulations. When other networks are simulated, the results will most likely show different particularities however. This also requires a different communication strategy. Additional feasible strategies should therefore be explored as well. Examples of this are: dedicated lanes per vehicle type, time slots for vehicle types or real-time communication of the traffic status (only testable in a large network).
- **Simulate different vehicle compositions**: In this research only scenarios were simulated that mixed one type of CAV with conventional vehicles. It is inevitable however that vehicles with different levels of automation will be present in the vehicle fleet at the same moment in time. It is therefore recommended for future research to simulate traffic scenarios in which the different levels of automation have to interact with each other.
- **Study individual vehicle parameters**: The three different CAV driving logics used in this study, as formulated by Olstam and Johansson (2018), are made up of 25 individual parameters. The simulations only show the results of these three specific combinations of these 25 parameters, but is not able to estimate the effects of each individual parameter. It is therefore recommended to study the effects of these parameters more into detail so that more well estimated predictions can be made regarding the effects of newly formulated driving logics.
- **Reconsider the cautious CAV formulation**: It is advised to revise the cautious CAV formulation for highway scenarios. In a signalized urban traffic environment, a formulation that never takes risks can be feasible since traffic is more turn-based in such environments. However, in highway traffic with large traffic intensities this driving logic leads to indecisive behaviour by the cautious CAVs which leads to inadmissible effects on traffic efficiency and safety. This research direction can also involve developing new types of CAV driving logic.

- **Study effects of physical infrastructure**: One major assumption of the simulations was that connected and automated vehicles are able to pass through work zones, regardless of the large irregularities in physical infrastructure. In literature it is known that this is often not the case however. García and Camacho-Torregrosa (2020) and García et al. (2020) show that features such as reduced lane width and sharp curves in the road still have major implications on the functioning of CAVs. Additionally, Ulrich et al. (2020) have formulated a list with elements that are of interest for automated driving. Most of these physical effects could not be studied using a simulation method such as the one used in this research. The effects of individual physical infrastructural elements, such as those presented in appendix B, should therefore be further studied. This can be done with field operational testing.

By filling these research gaps road work companies, road operators and NRAs can make sure that they are prepared better for a future with automated vehicles. This can help in the smooth implementation of these vehicles, and prevent major safety deficiencies.

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A

Scientific paper

The impact of Connected and Automated Vehicles on highway work zone traffic efficiency and safety

A simulation study

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Abstract

The emergence of connected and automated vehicles (CAVs) could have a significant impact on traffic efficiency and safety. The effects of CAVs in regular highway traffic are relatively well represented in scientific research. How these effects change in exceptional situations, such as work zones, and how the infrastructure can influence these effects is unknown however. Therefore, the main goals of this study are (1) to better understand the potential impacts of CAVs on traffic efficiency and traffic safety in highway work zones under different circumstances, and (2) to make a well formulated estimation of how current communication in work zones will need to be changed in the future. Two highway work zones were simulated in VISSIM. Three different types of CAVs (cautious, normal & all knowing) were implemented, each at 5 different penetration rate levels (0-100% with steps of 25%) in combination with conventional human operated vehicles to assess the traffic efficiency and safety effects. The traffic demand was kept constant at a theoretical F/C-ratio of 1. Based on first observations two communication strategies were added to the networks aimed at CAVs. These were (1) an early merge strategy and (2) an increased headway strategy. It was concluded that cautious CAVs have a negative effect on traffic efficiency and safety. The magnitude of these effects increased as the penetration rate increases. As CAVs became more aggressive, the traffic efficiency was increased. The traffic safety was deteriorated however, as a result of short time headways. The two communication strategies showed great potential to relieve the congestion in cautious CAV scenarios and to increase safety when entering the work zone.

Keywords: Connected and Automated Vehicles (CAVs), Simulation, Traffic safety, Traffic efficiency, I2V

1. Introduction

In recent years, vehicle automation technologies have significantly advanced. Car manufacturers equip their new models with automated functionalities. The features vary from self-parking systems to crash avoidance systems such as automated braking, lane departure warning systems and forward collision warning systems. As these technologies become more common, countries start taking their own steps to get ahead in knowing what is to be expected of these technologies. In this light Automated Vehicle(AV) testing has been legalized in several different parts of the world including the US, Austria, Australia and China (Morando et al., 2018).

The large interest from governmental agencies in these new technologies is for good reason. In the Netherlands alone, the number of traffic fatalities per year has remained constant in the last two decades (van Asselt, 2019). Opposite to this, the Dutch government and the European Union have set the goal of 0 traffic fatalities in the year 2050. AVs are generally believed to increase traffic safety significantly since most accidents are related to human error, although the magnitude of the reduction varies across literature (Chan, 2017, Shladover, 2009). Traffic efficiency is expected to benefit from vehicle automation as well. When all vehicles are automated, the traffic efficiency is believed to be the highest as a result of features such as smaller time headways, more constant driving speeds and quicker reaction times (Calvert et al., 2017, Liu and Fan, 2020, Mehr and Horowitz, 2020, Penttinen et al., 2019).

Promising new technologies often introduces new issues. In the long transition period in which AVs and conventional human road users use the roads alongside each other, AVs can not be expected to improve safety directly. Numerous fatal accidents have occurred already in which the automated driving system(ADS) was found to be active (Green, 2020, Gärtner, 2020, Lambert, 2019).

Road operators are starting to realize that there is a need to adapt the infrastructure to ensure safe and efficient traffic during the transition period. EU funded projects such as INFRAMIX (Berrazouane et al., 2019, Carreras et al., 2018, Erhart et al., 2019, Lytrivis et al., 2018a,b, Markantonakis et al., 2019) and MANTRA (Aigner et al., 2019, Penttinen et al., 2019, Ulrich et al., 2020, van der Tuin et al., 2020a,b) have emerged to research the changes that are needed. Several high risk traffic scenarios were formulated for AVs in these studies. Among these high risk scenarios is the scenario of roadwork zones. Infrastructure to vehicle (I2V) communication, enabled by wireless communication networks such as Wifi or 5G (or newer iterations), is suggested as a means to make safe en efficient traffic possible (Kulmala et al., 2019, Marshall, 2017). Both the infrastructure and the AVs have to be connected for these means of communication to work. To this end, the concept of Connected and Automated Vehicles(CAVs) was developed.

Lytrivis et al. (2018a), Wen (2018) and van der Tuin et al. (2020b) studied possible ways to influence the traffic efficiency and safety in work zones with different strategies of I2V communication. Lytrivis et al. (2018a) conducted a uses case based analysis to identify challenges for CAVs and to provide solutions to these challenges. Several use cases were dedicated to roadwork zones. It was however identified that due to a lack of insight into automated vehicle behaviour feasible solutions were hard to formulate. More insight into this behaviour is thus required. Wen (2018) executed microscopic simulations in work zones to make travel time predictions without adding ways to influence these travel times. The study simulated one work zone type with 100% CAVs penetration rate. More work zones and different penetrations rates should be simulated to gain a better understanding of the impacts of CAVs. van der Tuin et al. (2020b) simulated two different moving work zones (safety trailer and winter maintenance truck) at different penetration rates of CAVs (0-100% with steps of 25%). In these moving work zone simulations, one type of CAV driving behaviour was simulated and an early merging strategy was communicated exclusively to CAVs. The study concludes by stating that more work zones should be studied and that additional communication strategies should be examined.

Based on the recommendations of earlier studies, this study examines three CAV driving behaviours at five penetration rates in two static work zones to observe the effects of traffic efficiency and safety. Based on the first observations, two new communication strategies are tested in these work zones to improve the traffic performance.

Research objectives

This research uses microscopic simulation to estimate the effects CAVs will have on the traffic efficiency and traffic safety in highway roadwork zones. Traffic efficiency is explained in this research as the extent to which a traffic system can meet the travel demand of people in that system (Gaitanidou and Bekiaris, 2012). The research goals of this study are twofold:

1. To better understand the impacts of CAVs on the traffic efficiency and traffic safety in highway roadwork zones in different scenarios.
2. To make a well formulated estimation of how current communication in work zones will need to be changed in the future.

The following sections of this paper are organized as follows: Section 2 presents the conceptual model that is formulated based on literature. In Section 3 the simulation methodology that is used is presented after which the results of the simulations are presented in Section 4. Section 5 places these results in context, after which Section 6 summarizes the findings of the research and presents directions for further research.

2. Conceptual model

Figure A.1 presents the causal diagram that was constructed based on literature. This causal diagram is made for to help formulate the simulations later and help identifying the research gaps. It is also used to indicate the scope of this research. The dotted square represents the traffic system. The gray factors on the left represent external factors. The black oval factors are the system factors. On the right side, the system output is presented in blue. Finally the orange factors on top present the future developments with relation to automated driving. Green arrows indicate positive relations(i.e. when A increases, B increases) and red arrows indicate negative relations(i.e. when A increases, B decreases). Note that the terms *positive* and *negative* do not mean good or bad in this context. All factors in the model are included in the simulations as an input, as a scenario factor or as an output. The gray and black factors with thin borders are factors that are used as input factors. The black factors with thicker borders are used as the Key Performance Indicators(KPIs), since safety and efficiency themselves are not measurable. The orange factors the scenario factors. The most noteworthy features that can be identified are discussed in the following sub-sections.

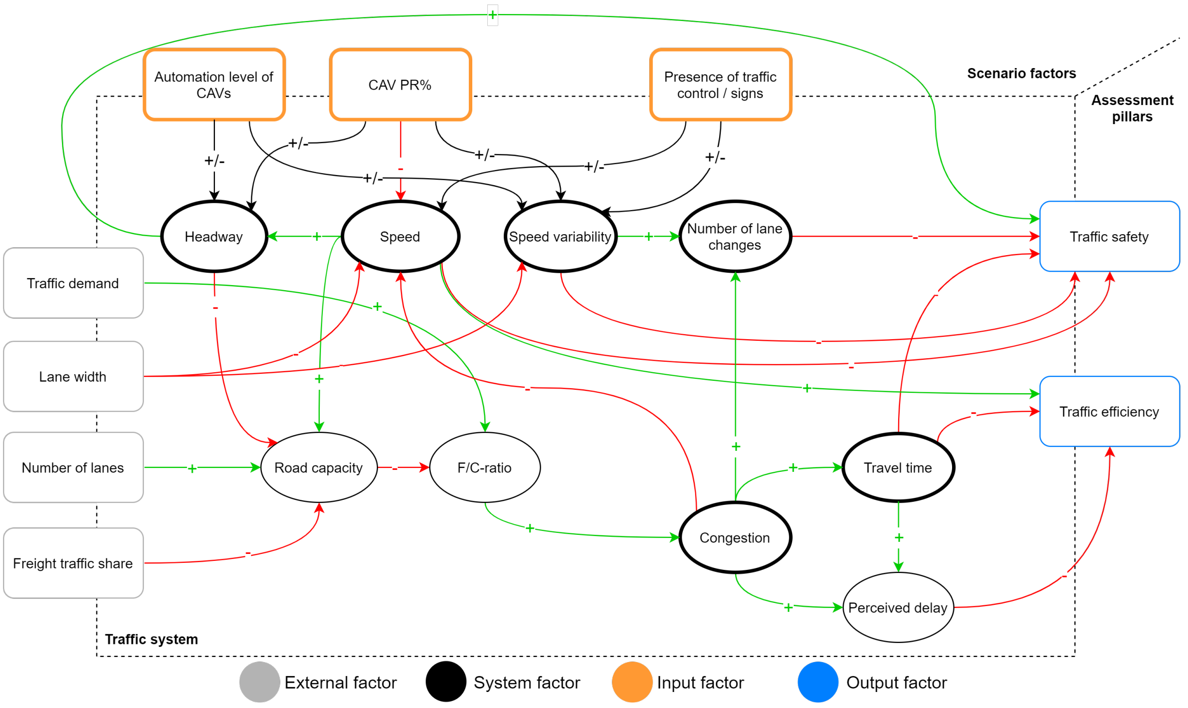


Figure A.1: Causal diagram

2.1 Feedback loops

The first feedback loop is made up of speed, road capacity, F/C-ratio and congestion. This positive feedback loop shows that as congestion forms, the speed drops which reduces capacity even more which increases congestion even more. The second feedback loop is a negative feedback loop. This negative feedback loop is made up of headway, road capacity, F/C-ratio, congestion and speed. This loop shows that as congestion forms, the headways are reduced, which increases road capacity, which relieves congestion slightly. This second feedback loop therefore relieves the effects of the first one. Note that the external factor of traffic demand is very important here to neutralize the congestion.

2.2 Uncertain relations

The effect that the level of automation of CAVs will have on the average headway and speed of all traffic is uncertain. This relates to interactions between CAVs and conventional vehicles. Therefore, the automation level of CAVs has an uncertain impact on the headway and the speed variability. This same principle holds for the CAV penetration rate. The effect of the penetration rate on the headway is uncertain. At a 100% penetration rate the headway can be predicted very well, but the effects of the CAVs on conventional drivers in uncertain. That is why the effect of CAV penetration rate on headway is uncertain. This is the same for speed variability. At a 100% penetration rate the speed variability is very small. At lower penetration rates the effect is uncertain however.

The effect that the presence of traffic control/sign will have on the traffic system is highly dependent on the type of control or sign. Zheng et al. (2010) stated that this variable increases traffic efficiency and safety. The way in which traffic safety and efficiency are influenced however is uncertain because this is dependent on the type of control. In figure A.1 this factor is shown to influence speed and speed variability, but it could influence many other factors in the system such as headway or lane changes.

3. Methodology

This section presents the four building blocks of the microscopic model that is used. Section 3.1 presents the basic networks that are used. Section 3.2 formulates the different types of driving behaviour that are present within the simulations. Section 3.3 presents the structure of the scenarios and section 3.4 presents the Key Performance Indicators(KPIs) on which the scenarios are assessed.

3.1 Network set-up

Two networks were selected that both contained a very simplistic representation of a typical roadwork zone configuration. The selection of work zone configurations was based on literature and a workshop that was held with the VolkerWessels traffic management team at VolkerWessels Infra Competence Centre. The two work zones that were selected are a right lane closure, and a 3-1 contraflow system.

The general lay-out of a right lane closure is presented in figure A.2. This network was implemented in VISSIM based on the Dutch national guidelines (CROW, 2020). The network contains features of interest such as speed reductions, a bottleneck and a road section containing only one lane. CAVs are programmed differently from conventional vehicles, so different behaviour is observable.

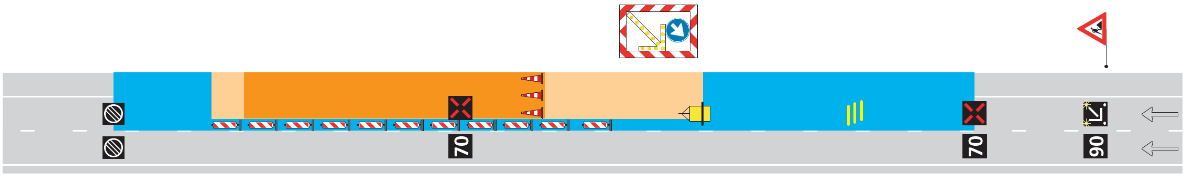
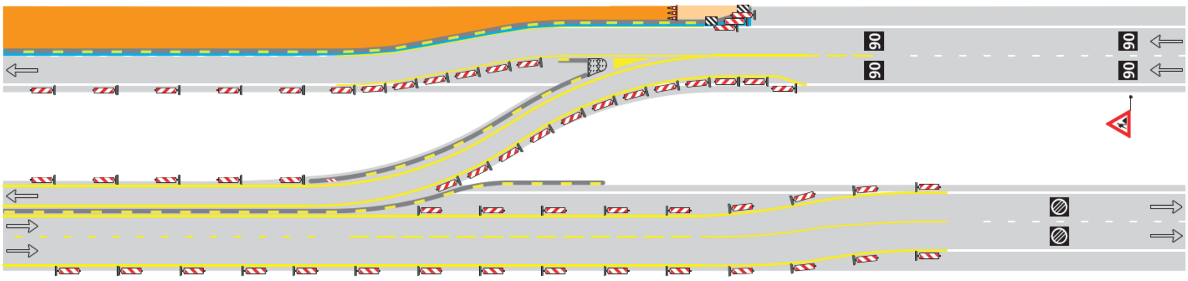
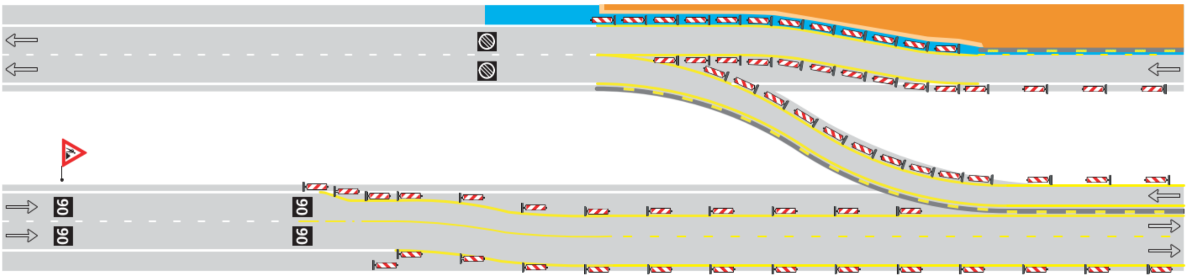


Figure A.2: Right lane closure (CROW, 2020)

Figure A.3 represents the 3-1 contraflow system. The two sub-figures together form the traffic system. It was implemented in VISSIM based on the Dutch national guidelines (CROW, 2020). The features of interest include a speed reduction, two lanes that split and lane width reductions within the work zone. In these areas the CAVs are likely to behave differently from conventional vehicles. The effect of a lane width reduction could not be captured in simulation. It is therefore difficult to estimate these effects.



(a) Start of 3-1 system: Vehicles from the right are distributed over both driving directions



(b) End of 3-1 system: Vehicles from the right are redirected back to their own driving direction

Figure A.3: 3-1 contraflow system (CROW, 2020)

The highway sections were modelled as a section with 2 lanes and a maximum speed limit of 100 km/h. The corresponding capacities that were used are 1725 pcu/h for the right lane closure, and 3450 pcu/h and 3910 pcu/h for the two directions in the 3-1 contraflow system. These capacities represent a theoretical F/C-ratio of 1 based on empirical capacity values that were found by Henkens et al. (2015). The road works were simulated without any additional on- or off-ramps. The speed reductions were placed based on the Dutch CROW (2020) standards, and vehicles are assumed to only speed up after the work zone has ended.

3.2 Vehicle driving logic

Four different types of vehicles were simulated throughout all simulations. These include three different types of CAVs and one type of conventional vehicle (i.e. driven by a human). It is advised by PTV to use calibrated driving behaviour models instead of the VISSIM default model. For the conventional vehicles (CVs) the driving behaviour formulation was therefore based on research by van Beinum et al. (2018) who formulated a calibrated driving behaviour for a crowded traffic environment on a weaving section in the Netherlands. This includes changes to the Wiedemann 99 car-following model. Even though the work zones do not contain weaving sections, the driving behaviour is assumed to be representative since the rest of the environment (e.g. crowded, mandatory merging because of the bottleneck) are similar.

For the CAVs three different types of vehicles were simulated that use the driving behaviour as were formulated by Sunkennik et al. (2018). There is still uncertainty surrounding the behaviour of CAVs. Therefore Sunkennik et al. (2018) formulated three CAV driving behaviours: Cautious, Normal and All knowing. Cautious CAVs are typified by the desire to never cause accidents (Olstam and Johansson, 2018). This is shown in settings such as the enforcement of the absolute braking distance, a severely increase headway and smoother acceleration and braking. Normal CAVs are formulated to mimic human drivers. Most settings are similar to the VISSIM default, but stochasticity in the behaviour is eliminated. This is true for all CAVs. All knowing CAVs are formulated to mimic a highly advanced CAV. This is typified by settings such as a very high number of interaction object, a longer look ahead distance and harder acceleration and braking. Apart from the driving behaviour, also the functions and distributions of CAVs were changed from the conventional vehicles. An example of this is that the desired speed value was set to 98-102 km/h, as opposed to the default of 88-130 km/h. The main differences between the different vehicle types are presented in table A.1.

Table A.1: Driving behaviour: Cautious, Normal and All knowing Sunkennik et al. (2018) & Calibrated CV van der Tuin et al. (2020b)

Parameter	**Cautious**	**Normal**	**All knowing**	**Calibrated CV**
Number of interaction objects	2	2	10	8
Number of interaction vehicles	1	1	8	99
Look ahead distance (min – max, m)	0-250	0-250	0-300	0-250
Look back distance (min – max, m)	0-150	0-150	0-150	0-26.16
Enforce absolute braking distance	Yes	No	No	No
Use implicit stochastic	No	No	No	Yes
Cooperative lane change	Yes	Yes	Yes	No
CC0 – Standstill distance (m)	1.5	1.5	1	2.33
CC1 – Headway time (s)	1.5	0.9	0.6	0.5
CC2 – Following variation (m)	0	0	0	3.91
CC3 – Threshold for entering ’following’ (s)	-10	-8	-6	-9.87
CC4 – Negative ’following’ threshold (m/s)	-0.1	-0.1	-0.1	-1.21
CC5 – Positive ’following’ threshold (m/s)	0.1	0.1	0.1	1
CC6 – Speed dependency of oscillation (rad/s)	0	0	0	11.44
CC7 – Oscillation acceleration (m/s2)	0.1	0.1	0.1	0.24
CC8 – Standstill acceleration (m/s2)	3	3.5	4	3.50
CC9 – Acceleration with 80 km/h (m/s2)	1.2	1.5	2	1.50

3.3 Simulation scenarios

As mentioned, two networks were modelled. These networks are the right lane closure and the 3-1 contraflow system. Three types of CAV driving logic are modelled. These are the cautious, normal and all knowing driving logic. The CAVs are modelled at five different penetration rates (from 0 to 100%, in steps of 25%). The two base scenarios account for the 0% penetration rates. Per network, twelve (three CAVs and four PR%) additional scenarios were created to account for the variations in CAVs and penetration rates. This leads to a total of 26 scenarios that were analyzed, as can been seen in figure A.4. These 26 scenarios are all run 11 times.

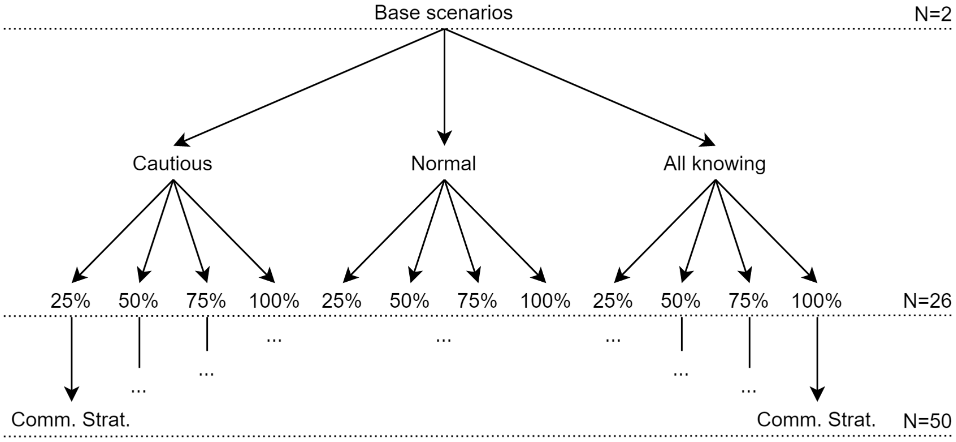


Figure A.4: Scenario design

After analyzing the first 26 scenarios, the communication strategies that are aimed at aiding traffic efficiency and safety were implemented in the simulation scenarios. These communication strategies were defined based on the findings of the analysis of the first 26 scenarios. Adding these communication strategies to the scenarios (except the 0% penetration rate) leads to 24 additional scenarios. In total, this implies running 50 different configurations.

3.4 KPI specification

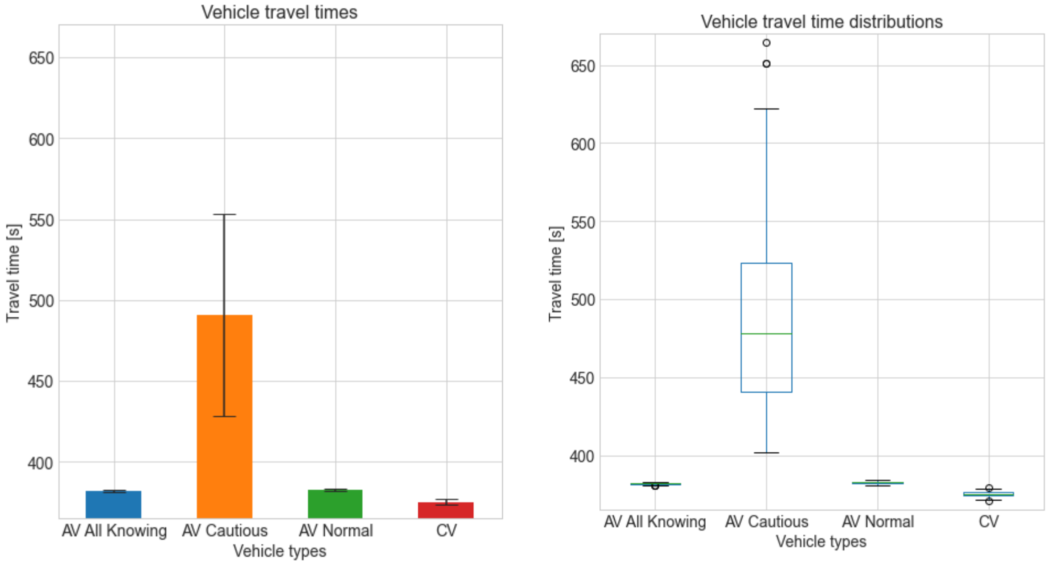
Based on the findings of the conceptual model, the KPIs were determined. The full list is presented in table A.2. Travel time, queue length and average speed were used as KPIs for efficiency. Although these factors are related to each other, they were chosen to obtain a complete image of what the effects of CAVs are. Travel time and average speed were not expected to change drastically with different CAV penetration rates. This was expected because the speed distributions of CAVs do not allow for speeding. The queue length was expected to differ between scenarios. With more advanced CAVs it was expected that queues are shorter(if formed at all), since their behaviour allows for much faster queue dissolving. Cautious CAVs were expected to experience difficulties with merging leading to increased queues. The speed variability, time headways and number of lane changes were used as KPIs for safety. The speed variability is related to crash severity. Larger speed differences make crashes more severe. Time headways are related to the crash rate. Shorter time headways leave less reaction time. At 100 km/h a time headway of 2 seconds is advised for passenger cars (SWOV Institute for Road Safety Research, 2012). Lane changes are known to be risky maneuvers and they indicate turbulence in traffic. More lane changes generally indicate more unsafe traffic. All CAVs were expected to increase safety. This is because speeds become more homogeneous with an increased number of CAVs, which would subsequently lead to fewer lane changes. More advanced CAVs keep shorter headways, but this is compensated by their reaction time.

Table A.2: Key performance indicators

Traffic efficiency		**Traffic safety**	
KPI	**Unit**	**KPI**	**Unit**
Travel time	[sec]	Speed variability	[km/h]
Queue length	[m]	Time headways	[s]
Speed	[km/h]	Lane changes	[#]

4. Results

The traffic efficiency related findings showed that as the penetration rates of CAVs increased, the average travel times increased as well. Figure A.5 presents the travel times of 100% CAVs and CVs only. Conventional vehicles performed better than the CAVs although the differences with normal and all knowing CAVs were only very small (< 3%). This can by explained by the modelling assumption that CAVs stick to the speed limit, where human drivers often drive faster than the speed limit. The cautious CAVs showed a vast increase of the travel times in the right lane closure network.

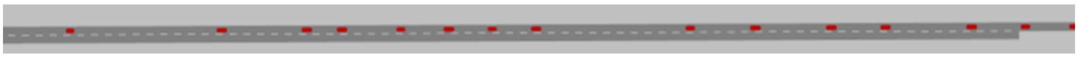


(a) Vehicle travel time averages with standard deviations

(b) Vehicle travel time distributions

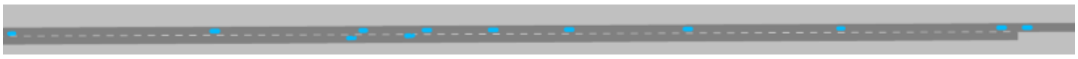
Figure A.5: Vehicle travel times and distributions at 0% and 100% CAV penetration

This is a result of the large queues that formed on the right lane in front of the work zone in this network. Because cautious CAVs do not want to take risks they were unable to execute a lane change in busy traffic. This led to a traffic situation in which the right lane was congested, while vehicles on the left lane continued to drive at cruising speed. Screenshots of this road section are presented in figure A.6. The 3-1 contraflow simulations did not show any congestion for any of the scenarios, so no large travel time differences occurred there.

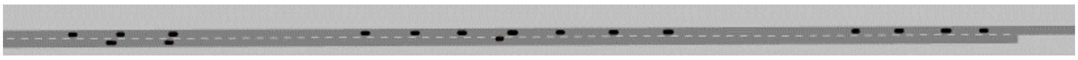


(a) 100% All knowing

(b) 100% Cautious



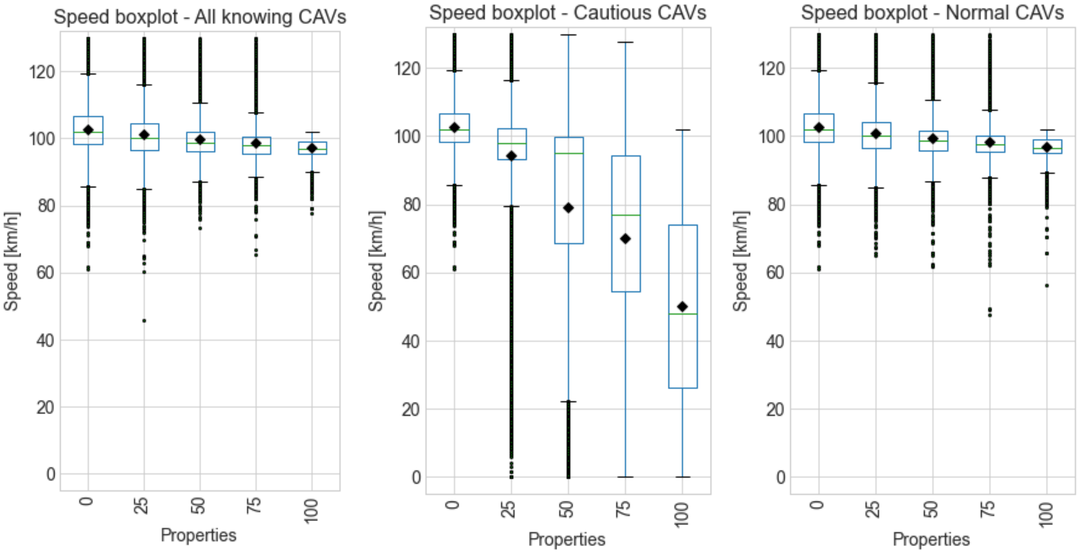
(c) 100% Normal



(d) Conventional vehicles

Figure A.6: Screenshots of VISSIM 11 showing the traffic situation right before the bottleneck at a right lane closure

The traffic safety related findings show that normal and all knowing CAVs increase safety the most. Speed variability (figure A.7) is lowest with these two vehicle types. This is a direct result of the assumption that these vehicle stick to the speed limit. The number of lane changes was also reduced significantly. The headways maintained by these two CAV types are shorter which could in reality lead to negative safety implications. Cautious CAVs perform well when looking only at the maintained headways and the number of lane changes, but the speed variability is very large in this scenario. This is a result of the congestion that forms on the right lane.



(a) All knowing (b) Cautious (c) Normal

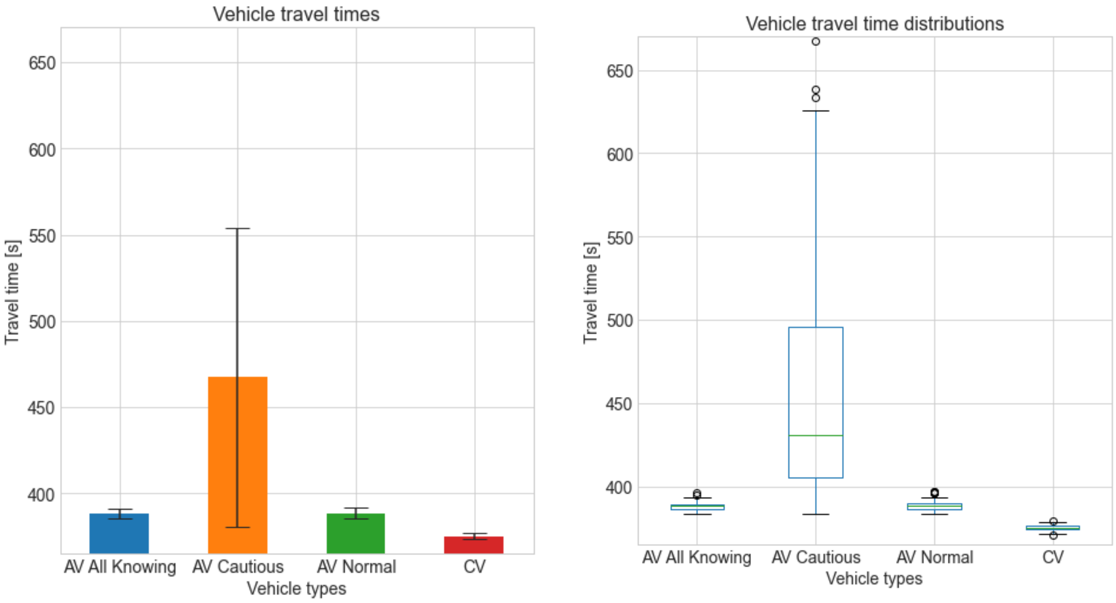
Figure A.7: Speed variability boxplots grouped by scenario on the road section right before the right lane closure

The results of the scenarios show that as the CAV penetration rates increase the magnitude of the aforementioned (positive and negative) effects increases as well. Travel times become (slightly) longer, average speeds are reduced and the queues that form with cautious CAVs increase. Speed variability is reduced more as the penetration rates increase and the number of lane changes is reduced. It is found that normal and all knowing CAVs cause short headways in the transition areas into the roadwork zones. This could severely harm the traffic safety in these locations.

4.1 Communication strategies

Two communication strategies were formulated. The goal of these two communication strategies is to relieve the negative effects that the CAVs have on traffic efficiency and safety, while maintaining the positive effects. The first communication strategy is an early merging communication strategy that is aimed at relieving the congestion that formed in scenarios with cautious CAVs. CAVs are told 2 kilometers ahead of the work zone that they are required to switch to the left lane so that they do not get stuck right in front of the work zone as they were in figure A.6. The second communication strategy that was formulated is a signal that tells CAVs to adapt the headway of a cautious CAV on the road section ranging from 500 meter ahead of the work zone until the end of the work zone. This strategy is aimed at easing the transition into the work zone and the traffic situation within the work zone itself.

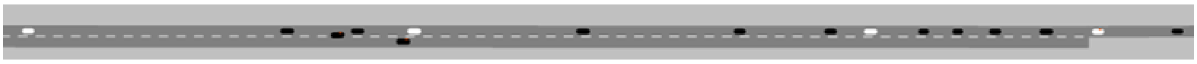
The implementation of the communication strategies affects the travel times in different magnitudes. The travel times and distributions per vehicle type are presented in figure A.8. It was found that the average travel times in the cautious CAVs scenarios were reduced from 491 seconds to 468 seconds. The travel time standard deviation had on the other hand increased from 62.4 seconds to 86.6. This indicates an even more wide average speed distribution than found earlier. The travel times observed in the normal and all knowing CAVs scenarios had slightly increased as a result of the longer headway that was communicated to the vehicles within the work zone. This effect is only marginal however. Both normal and all knowing CAVs take 388 seconds to clear the network with added communication, where they did this in 383 and 382 seconds without it. Both travel time standard deviations are increased as well to 3.1 and 2.5 seconds. The travel times are thus distributed slightly wider, but this effect is only very small.



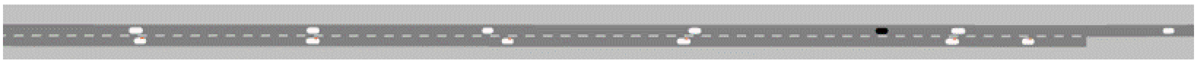
(a) Vehicle travel time averages

(b) Vehicle travel time distributions

Figure A.8: Vehicle travel times and distributions at 0% and 100% CAV penetration with early merge and increased headways



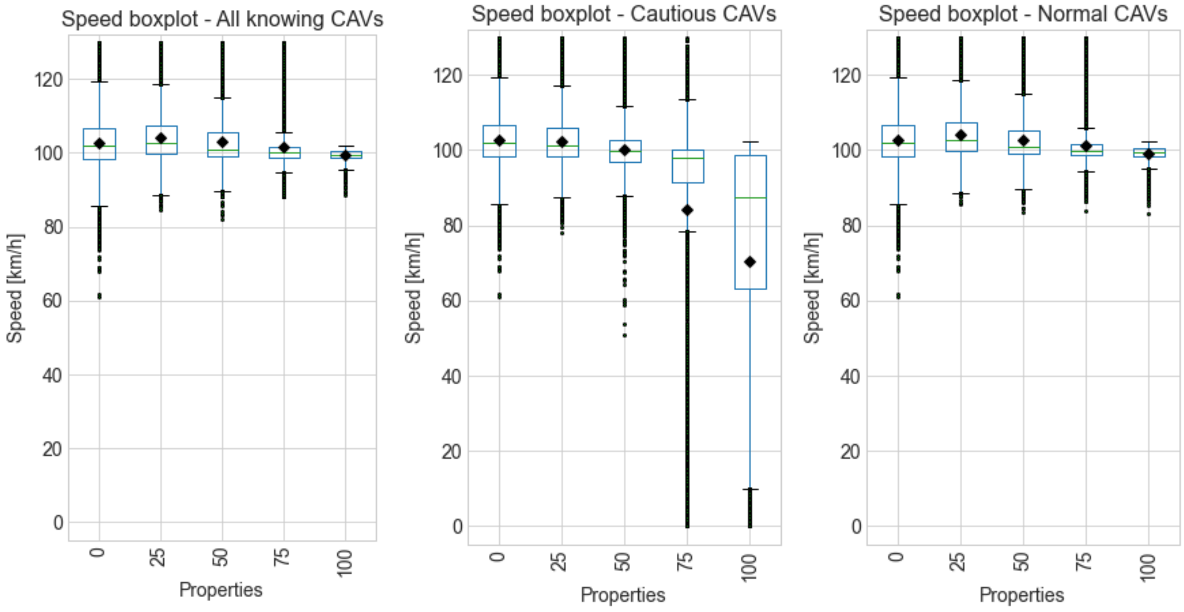
(a) 25% cautious CAVs



(b) 75% cautious CAVs

Figure A.9: Screenshots of VISSIM showing the traffic situation right before the bottleneck with cautious CAVs(white) and CVs(black) at a right lane closure with early merge and increased headway enabled

The early merging strategy only works at a 25% and 50% penetration rate. This is illustrated in figure A.9. The top figure shows a traffic situation with 25% CAVs, and the bottom situation shows a situation with 75% CAVs. With lower CAV penetration rates, the CAVs are told on time that they have to switch to the right lane. They do this while the CVs remain distributed over both lanes. With higher penetration rates the CAVs are told to change to the left lane at the same moment as in the other scenarios, but because there are a lot more CAVs in the network the left lane becomes cluttered. This leads to major congestion at higher cautious CAV penetration rates. With lower penetration rates the traffic efficiency is improved severely however compared no communication.



(a) All knowing

(b) Cautious

(c) Normal

Figure A.10: Speed variability boxplots grouped by scenario on the road section right before the right lane closure with early merge and increased headway enabled

Figure A.10 shows that the speed variability is reduced with the communication strategies compared to no communication. With lower penetration rates all CAVs perform better on both traffic efficiency and safety. Average speeds are increased, and speed variability is reduced. It is clearly visible that the communication strategies with 75% cautious CAVs are very unsuccessful. This can be explained however by the phenomena that were mentioned earlier. With the implementation of the strategies the number of lane changes is vastly reduced as well and the overall time headways are increased compared to the situation with no communications.

5. Discussion

Many assumptions were made in constructing the simulations that were used in this research. These are discussed in the following sections. Section 5.1 presents the limitations regarding the simulated networks. Section 5.2 states the limitations than come with the simulated driving behaviour after which Section 5.3 discusses the limitations of the results of the communication strategies.

5.1 Simulated networks

There are many factors that impact the capabilities of CAVs to read the road ahead of them. These include factors such as consistent road markings, consistent road signs and not too many signs in close succession which are already three phenomena that are in practice inherently linked to road works and work zones. In order to assess the impacts of CAVs on a microscopic level, the major assumption was made that CAVs are able to drive through work zones. Secondly, the work zone design of the 3-1 contraflow system includes reduced lane width areas. García et al. (2020) and García and Camacho-Torregrosa (2020) found the lane width and curvature of the road to severely influence vehicle performance. The effects of curves and reduced lane width areas are not taken into account by

VISSIM however. Thirdly, in the simulations, the 3-1 contraflow network contains one origin and one destination. This means that vehicles do not have to choose one of the two directions at the separation in order to reach a specific destination. In reality, 3-1 contraflow systems are mostly implemented on sections of road where there is an on- and/or off-ramp that is essential for traffic in the area. Adding an off-ramp to the network would severely alter the results.

5.2 Simulated vehicle behaviour

Three distinct parameter sets were formulated based on Olstam and Johansson (2018) to simulate CAV behaviour. These sets included 25 individual parameters and changes to the distributions. From literature we know that not all parameters have the same impact on the shown behaviour in simulation. However, based on the simulations that were executed it is very difficult to draw conclusions regarding individual vehicle parameters. Additionally, the way in which CVs are formulated is highly influential on the results. The travel time results that were found in this study were consistent with the findings made by van der Tuin et al. (2020b) where calibrated CV driving behaviour was used. In additional tests that were done in that research where the VISSIM default driving behaviour was used for CVs, the travel time gains as a result of a larger share of CAVs was larger. This is also due to the headways that were maintained. The headways that were maintained by the calibrated cars of van Beinum (2018) are quite short, since these were calibrated for the Dutch road network with large traffic intensities (and possibly congestion). Although this is consistent with the situation that it modelled in this study, this is something that should be kept in mind when interpreting the results. These different behaviours would in reality influence each other. One would expect that different CAV types have different effects on the behaviour of CVs. These secondary interaction effects between driving behaviours are not a part of VISSIM however. A factor that would also be dependent on the behaviour of the vehicles, is the road capacity itself. The vehicle inputs were simulated through static inputs based on the capacity values as presented by Henkens et al. (2015), meant to simulate a F/C-ratio of 1.0. Overall it is very important to know what the effects of individual behavioural aspects of CAVs are in simulation. As simulation is an often used method to make estimations of the potential effects that these vehicles will have, these effects should be known better. The current formulation of cautious CAVs is infeasible to implement in traffic in real-life, because it has too many negative effects on traffic efficiency. Normal and all knowing CAVs are very similar in their output.

5.3 Simulated communication strategies

As was show in the results, the early merge communication strategy works to relieve the congestion that forms at lower penetration rates of cautious CAVs. It is hard however to extrapolate this finding toward situations with different driving behaviour. If CVs would be simulated with more cautious behaviour it is more than likely that the early merging of CAVs would lead to the CVs having trouble merging. This is not the case with the current CVs. However, some literature states that the earliest iterations of CAVs will maintain longer headways than human drivers to ensure safety (Berrazouane et al., 2019, Rios-Torres and Malikopoulos, 2017). This makes the case that such an early merging strategy could be feasible. This communication strategy can be tested with more distributed communication, and more different vehicles setting in order to test the robustness of such a strategy.

The adopting of an increased headway for CAVs in the final road section before the work zone showed to be a moderate success in the simulations. This communication strategy made the transition into the work zone more smooth in terms of speeds and headways than was observed without communication. In the simulations, CVs coped with the braking of CAVs fairly well which shows in the results. Headways are slightly longer and traffic flow is increased because vehicles brake less hard. This is however very dependent on the traffic compositions and vehicle behaviours in general. Also, some of the CAVs still tend to brake quite hard initially which leads to some vehicles still having a very short headway. To improve this communication strategy, and to test its feasibility better, the strategy should be combined with other behavioural changes. These can include changes to the maximum allowed braking settings and to the maximum acceleration. This changes the behaviour of the CAVs slightly, which can improve safety further.

6. Conclusions

This paper studied the impacts of CAVs on traffic efficiency and safety in different work zones in order to formulate feasible communication strategies that were subsequently tested and evaluated. The results showed that if CAVs are programmed to be too conservative when they are introduced on a larger scale, this will lead to major traffic efficiency drops in work zones. This leads to large travel times, but could potentially also lead to dangerous situations as a result of large speed differences if conventional human drivers are a part of the traffic fleet still. The extent to which this happens is however very depending on the driving behaviour of conventional vehicles as well.

Additionally, the results showed that CAVs with more aggressive behaviour, such as the all knowing CAVs, could lead to safety issues for conventional drivers since these vehicles take risks that would in reality not be possible. Simulations do not simulate accidents, but it is very likely that these would occur because of interactions between aggressive CAVs and conventional drivers.

Results showed that if an early merging communication strategy is implemented as an addition to the conventional means of communication, this results in an increase in traffic efficiency and safety. These results are not directly suited for extrapolation towards real-life traffic situations however. The robustness of this measure should first be tested extensively with other traffic compositions and driving behaviours before physical tests can be applied. Also this conclusion only holds for lower penetration rates of CAVs. At higher rates, the effects of communication are nullified.

The communication of a longer headway to relatively aggressive CAVs showed potential to increase safety, although increasing the headway alone is likely not enough to ensure safe interactions with conventional traffic. These more aggressive CAVs still tend to accelerate/decelerate harder than usual which could in reality lead to problems. These are not visible directly within the simulations, but would likely occur in real-life.

In general, road works should should be designed as consistent as possible in order to help the automotive industry expand the ODD of their automated vehicles. In the near future, the physical infrastructure is of most interest to CAVs, since they mainly rely on their sensors and are not digitally connected. When work zones cannot be designed to suit the needs of CAVs, warning signs are required to make road users aware to turn off their automation systems. For the roads in general, they will need to be maintained better then they currently are, since the early versions of CAVs solely rely on sensors. To be ready when the need arises, road authorities should consider if it is time to begin installing road side units (RSUs) that can be used for digital communication to connected vehicles. Connectivity in vehicles is a development that transcends automated driving. For conventional vehicles this is an addition that can be used to provide road users with real time information, but for the future of connected and automated driving it will most likely become an essential part of the digital infrastructure.

For future research it is advised to elaborate upon this research by simulating additional high risk scenarios, by experimenting additional communication strategies or by simulating different vehicles compositions. Additionally, the effects of individual vehicle parameters can be further studied. Although simulation was a good method to use for the goal of this research, it is not perfect. The effects of physical infrastructural elements could not be studies by using this method. It is therefore advised to conduct field operational tests to study the physical infrastructure more in depth.

B

ODD attributes

Table B.1: List of physical infrastructure attributes relevant for CAVs Ulrich et al. (2020)

Physical infrastructure attributes		
Infrastructure attribute	**Sub-attributes**	**Comment**
Road	Road type	Basic road types such as motorway, highway, street, private road indicate separation of carriageways, intersection arrangements, types of road users etc.
	Special road sections	Additional requirements for critical road sections such as tunnels, bridges, toll plazas etc.
	Separation of automated vehicles	Dedicated lanes or areas; permanent or temporary such as night time only
	Pavement of road	Ease of detection of the roadway
Speed range	Speed limit or recommendation	The speeds in which the automated driving system has been designed to function. Either static or dynamic speed limits/recommendations. Dynamic ones relate to traffic management
Shoulder or kerb	Wide shoulder	possibility to use as “safe harbour” if ODD ends
	Lay-bys or parking areas	as above
	Passenger pick-up/drop off areas	necessary for automated shuttles and robotaxis
Road markings	Existence of lane markings	Lateral positioning
	Visibility, machine-readability	Visibility to vehicle sensors
	Markings indicating use by automated vehicles	indicating of right to use or prohibition of use by highly automated vehicles
Traffic signs	Visibility, machine-readability	visibility to vehicle sensors
	Signs indicating use by automated vehicles	indicating of right to use or prohibition of use by highly automated vehicles
Road furniture	Landmarks	Static physical landmarks possible equipped by sensor reflectors or radio beacons or similar to support accurate positioning
	Gantries for road signs	Indicating of right to use or prohibition of use by highly automated vehicles
	Gates and barries	Access to dedicated lanes, roads or areas
	Road lighting	Support to automated vehicle’s vision system
Infrastructure maintenance	Winter maintenance (snow removal, de-icing)	Visibility of road markings and traffic signs in adverse weather conditions
	Road maintenance incl. road marking painting, clearing of vegetation	Quality and visibility of road markings and traffic signs
	Inspections of infrastructure	Inspections according to standardised test/inspection protocols for both physical and digital infrastructure

Table B.2: List of digital infrastructure attributes relevant for CAVs Ulrich et al. (2020)

Digital infrastructure attributes		
Infrastructure attribute	**Sub-attributes**	**Comment**
Communication	Short-range V2I	Communication at hot spots and road sections
	Medium and long-range V2I	Communication over road networks and corridors
	Medium and long-range V2I with low latency and wide bandwidth	Communication facilitating remote supervision of vehicles
Satellite positioning	Land stations	Improving accuracy of positioning in challenging areas
	Positioning support in tunnels	GPS repeaters or other solutions to provide accurate positioning also in tunnels
HD map	Maps of road environment including landmarks for cameras and sensors	Accurate positioning of the vehicle in the transport system, road and lane
Information system (digital layer of the HD map)	Real-time event, road- works, incident & other disturbances	Providing extended horizon beyond sensor range
	Digital traffic rules and regulations	Proving permanent and temporary rules of operation
	Geofencing information	Informing of access to specific roads, networks and areas and/or right of use of specific automated driving use case
	Availability of physical infrastructure	Real-time information of the availability and usability of the physical infrastructure required for ODD
Digital twin of road network	Digital twin of transport network & its environment	Provides the transport system information to the HD map
	Real time digital twin of the network managed including traffic flows	Enables simulation, modelling and tesyting of different traffic management measures in order to select optimal measure for vehicle flows
Traffic management	Road works management	Standardised markings and processes to maintain ODD
	Incident management	Standardised markings and processes to maintain ODD
	ODD management	Management of factors affecting the ODDs of vehicles using the roads
	Traffic management centre and processes	Adaption of the centres and processes to consider special requirements from automated vehicles and mixed fleets
Fleet supervision	Fleet monitoring and supervision centres	Remote monitoring and supervision of fleets, likely necessary for shuttles, robotaxis, roadwork trailers and maintenance vehicles

Table B.1 presents the pysical ODD attributes that were deemed most important in relation to connected and automated driving in the study by Ulrich et al. (2020). Table B.2 presents the digital ODD attributes. The main attributes are given and are subsequently split into sub-attributes. The right column gives a short description of what is meant by each sub-attribute and how it should be interpreted.

C

VWICC workshop description

On Thursday the 12th of June a workshop was organized for the Traffic Management team of VolkerWessels Infra Competence Centre via Microsoft Teams. The goal of this workshop was to determine which work zone types are likely to cause the most risks for Connected and Automated Vehicles(CAVs), and which work zones types are most interesting for VolkerWessels to study in the context of automated driving. The events of this workshop are described in the following sections.

General presentation

The work shop was opened with a presentation that described the findings of the literature study. The goal of this presentation was to make the participants of the workshop aware of what kind of factors are of importance for CAVs in work zones, and how work zones might affect the performance of CAVs. Participant were introduced to concepts such as physical infrastructure, digital infrastructure, the SAE automation levels for CAVs, the ISAD automation levels for smart infrastructure, and the Operational Design Domain. Note that a presentation such as this could influence the answers given by the workshop participants. Because of this the presentation was mainly limited to an introduction to these concepts to make sure these were clear to the participants, without giving a judgement of value to these concepts.

Work zones

The participants were presented with three main types of work zones. These included stationary work zones, dynamic work zones and work zone systems. Even though work zones systems technically are a form of static work zones, these systems were presented separately because of their overall complexity compared to simple static work zones. Three static work zones, two dynamic work zones, and two work zone systems were part of the workshop.

Static work zones

The three static work zones are presented in figure C.1. The top work zone is often applied when work is done on the shoulder such as mowing or maintenance to the barrier. No lanes are terminated, but the width of the lanes is reduced. Because of this the speed limit is only reduced to 90 km/h. The middle work zone closes off one lane and the shoulder. Only one lane remains. This work zone is often applied when maintenance is done on the lanes themselves, or when work is done on the shoulder with large equipment. Because the number of lanes is reduced, and because the work takes place close to traffic, the speed limit is reduced to 70 km/h. The bottom work zone is similar to the top work zone, but here the work takes place on the median strip or barrier. This means that the left lane is closed. Traffic is able to drive on the lane that remains and on the emergency lane for as long as the work zone continues. The speed limit is reduced to account for the workers that work close to traffic.

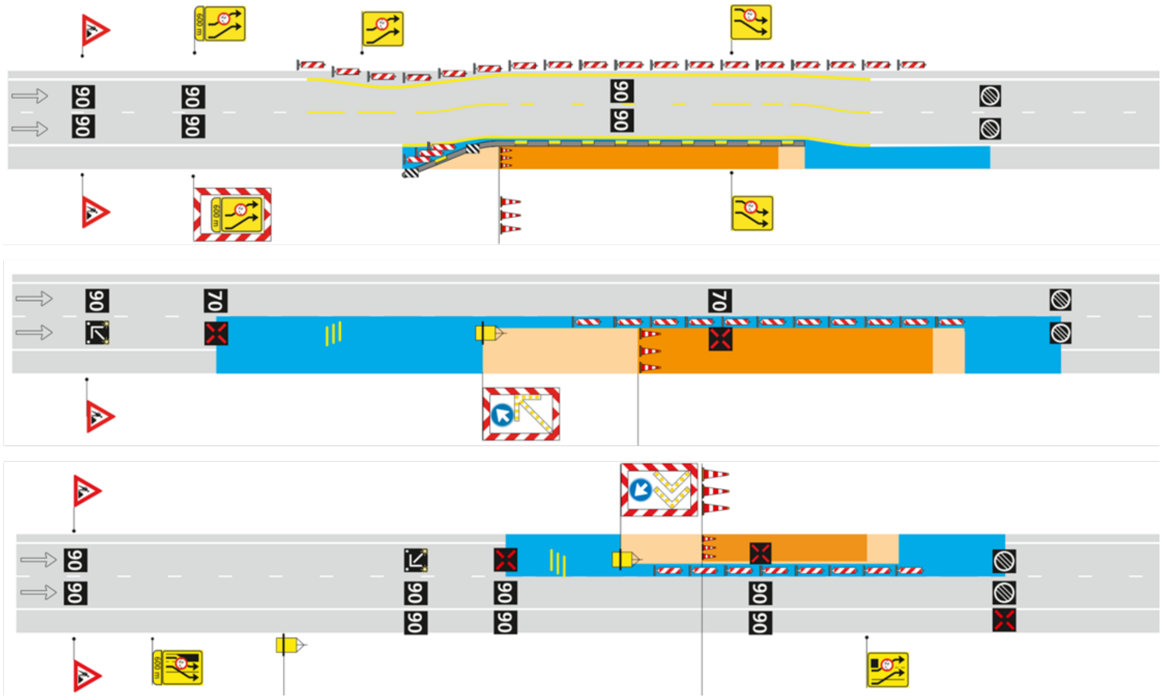


Figure C.1: Static work zones

Dynamic work zones

The two dynamic work zones are presented in figure C.2. The figures show two situations in which traffic in temporarily told to slow down and merge to pass the work zone that is moving. These types of work zones are often applied for road maintenance work that moves such as mowing, or maintenance to the road markings. The speed at which the road works move can vary based on the type of work that is done. The equipment used for the work itself is always accompanied by a safety vehicle that warns oncoming traffic. The top work zone shows a situation in which both the emergency lane and the right lane is closed for traffic. This type of dynamic work zone is applied for work such as the reapplying of the road marking. Because the number of available lanes is reduced the speed limit is reduced to 70 km/h. The bottom work zone shows a situation in which only the emergency lane is closed. Although the work does not take place on the lanes themselves, the safety vehicle is still present to prevent traffic from driving into the work zone. No speed limit reduction is applied.

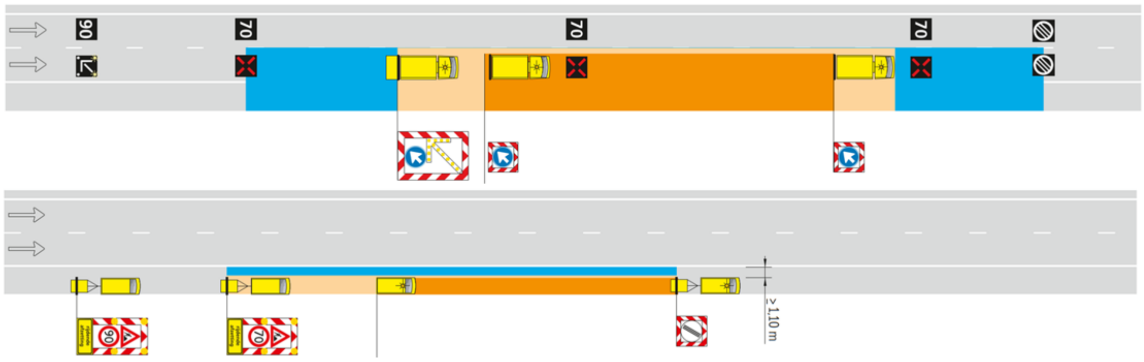


Figure C.2: Dynamic work zones

Work zone systems

The two work zone systems are presented in figure C.3. These systems are applied when large scale road works have to take place such as executing major maintenance work or making additions to the road network. In these cases, traffic can not drive alongside the work that takes place and is therefore moved to the opposing driving direction. The top figure presents a typical 4-0 system. This means that four lanes are used in one direction, and none in the other. The lane width is reduced in both driving direction and the the speed limit is reduced as well. This kind of system is often applied when work takes place on one side of the road, but closing that direction in its entirety would result in to much traffic delay. The bottom figure presents a typical 3-1 system. This means that three lanes are used in one direction, and one in the other. These type of systems are used in similar situations as the 4-0 system, but with the addition of an essential entry- and/or exit ramp. This system then account for the mobility of road users within the area of this ramp. Here a speed limit reduction is applied as well that set the speed limit at 90 km/h.

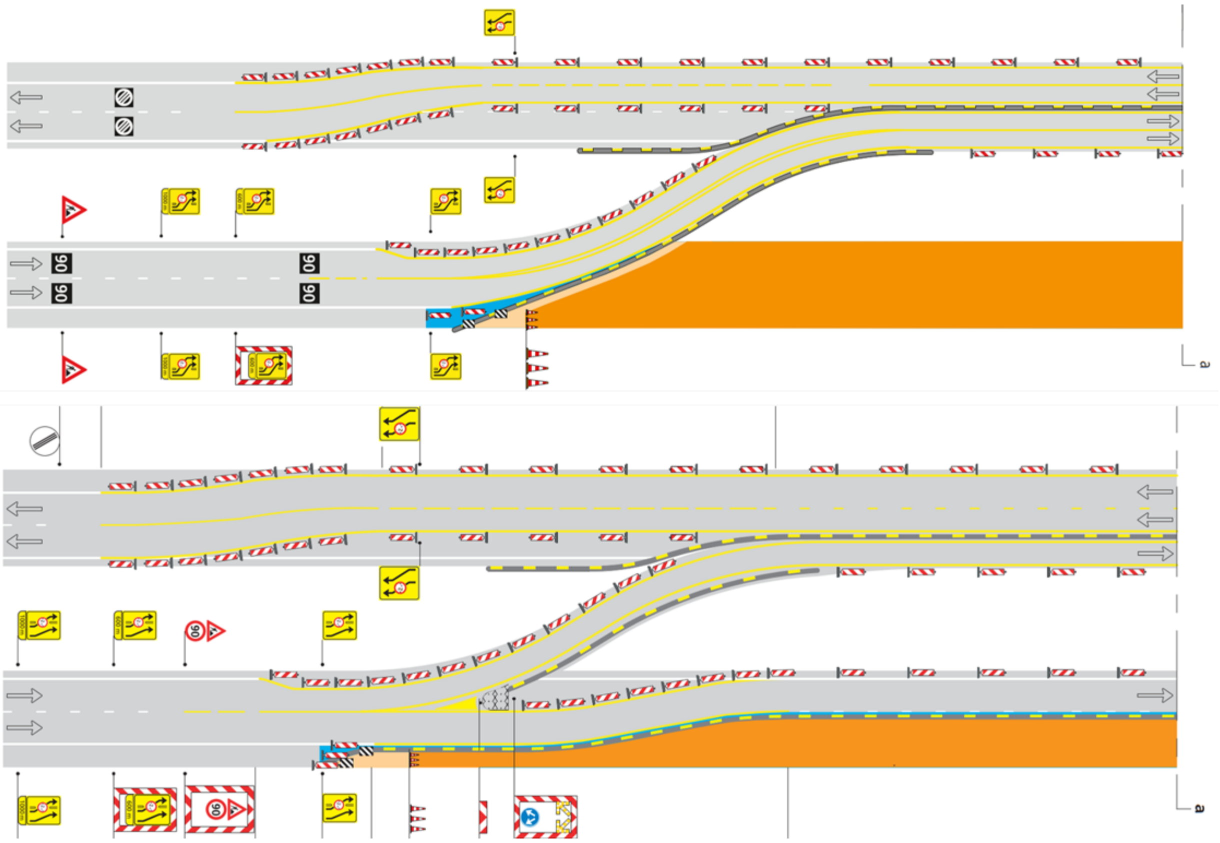


Figure C.3: Work zone systems

Rounds

After the introductory presentation and after the work zones were discussed the workshop consisted of three main rounds. Based on their experience gained in their work they were asked to answer one main question per round. In the first round, participants were asked what kind of risks they were expecting in the traffic area for each of the three work zones types. This is the area alongside the work zone itself. In the second round, participants were asked what kind of risks they were expecting in the transition area for each of the three work zones. This is the area that reaches from the first moment vehicles are made aware of the work zone through signalisation to the start of the traffic area. In the third and final round, participant were asked to propose possible solutions to the risks that were stated in the earlier two rounds. These rounds were aimed at making the participant think of the possible risks that might occur. After these three round an open discussion was held to determine which types of work zones would be most interesting to simulate.

Results

The results of round 1 showed that most risks that were expected relate to the question: ”Does a CAV recognize the work zone?”. This shows in factors such as yellow road markings, reduced lane widths, manually placed barriers and manually placed cones. Other risks that were identified relate to whether the CAV knows when the work zone really begins and where it ends, whether the CAV can handle the many signs that follow in close succession in 3-1 and 4-0 systems and whether CAVs can handle the sharp s-curves that are implemented in the road when changing to the other driving direction. The final risks that were expected within the traffic area relate to the interaction between CAVs and the road works taking place themselves. How do CAVs react to workers walking close to the road at high speeds? How do they react to pieces of equipment that are placed close to the road? Although this is not allowed, it does happen in practice sometimes.

The results of round 2 showed that most risks that were expected again relate to recognizing the announcements that are made regarding the work zone. Secondly the results showed that there was a lot of uncertainty related to how CAVs and human driver both behave in such situations and what this means in the end. Human drivers generally want to merge early when a work zone is announced. If CAVs recognize the work zone, they will not have to merge directly. This could lead to interesting interaction between vehicles. Generally, fewer risks were expected in this area except for these interactions. What was often mentioned as well was that some traffic manager did not expect any CAVs within the transition area, since most CAVs will be programmed to take a different route to get around the work zone.

The results of round 3 showed much relation to the literature on connected and automated driving. The solutions that were proposed in this round are also mentioned often in scientific research. A first solution to the risks in static work zones was aimed at having CAVs get around work zones entirely. By having them receive real-time information they could potentially only drive on regular road without work zones. Another solution that was often proposed is the solution to make work zones as standard as possible. This requires knowledge of what is important for a CAV to understand the work zones. A third solution that was proposed was a geo-fence that disables all automated driving systems to make humans drive their vehicles themselves, or to make dedicated lanes for CAVs that are fully fitted to their needs. An often mentioned solution to eliminate risks for the workers themselves was to use automation the make dynamic work zones that execute simple maintenance work fully autonomous.

Conclusions

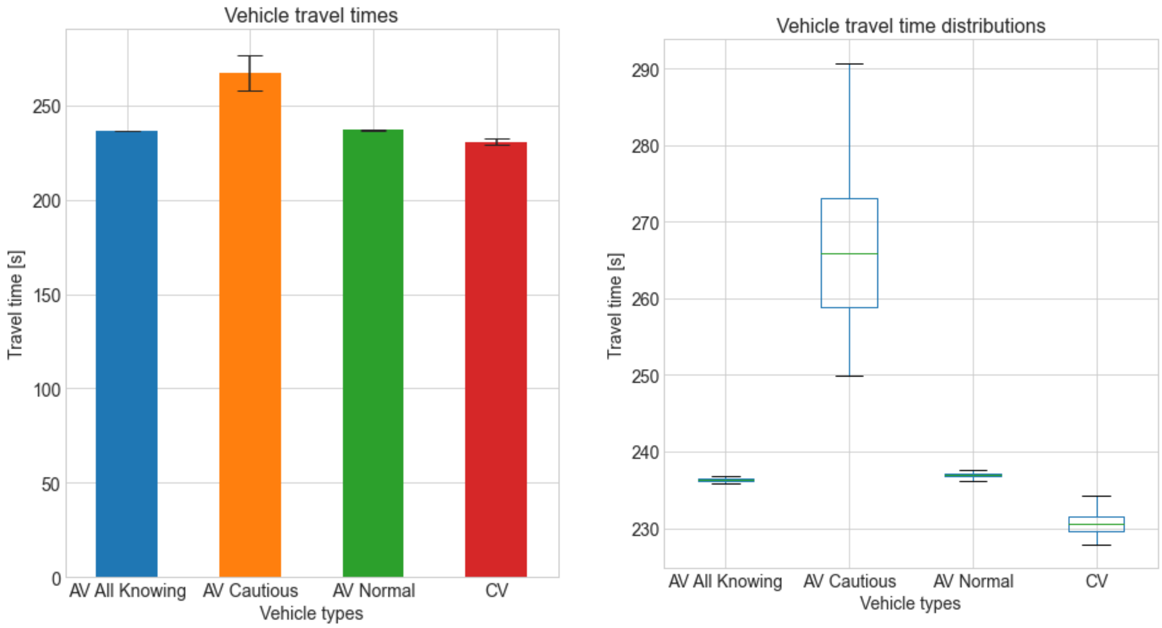
The general consensus after the three round was that there are still many uncertainties surrounding all types of work zones in relation to CAVs. The decision what work zone was most interesting to VolkerWessels was therefore mainly based on what kinds of work zones occur most often. Seeing that VolkerWessels almost never uses dynamic work zones in their work, this type of work zone was excluded from the selection. The meant that the static work zones and work zone systems were left. Both these work zones are of high interest to VolkerWessels, however the regular static work zones are implemented in practice much more often than the complex systems. Finally, the decision was made to study two work zones. The first work zone that was selected was the middle work zone in figure C.1. This selection was made because it is a work zone that occurs very often, but that is not too complex. To account for the complexity the second work zone was selected, which was determined to be the 3-1 contraflow system of figure C.3. Although this type of system is not used very often, it is very complex with a reduced lane width, a routing decision and a reduced speed area. The participants were therefore very curious how CAVs would perform in such conditions.

Seeing that these two choices also have not been simulated earlier in scientific research these to choices were deemed feasible to further study. This adds to the scientific knowledge, especially when new forms of communication are implemented within these work zones.

D

Contraflow system results

Travel time



(a) Vehicle travel time averages with standard deviations

(b) Vehicle travel time distributions

Figure D.1: Vehicle travel times and distributions at 0% and 100% CAV penetration

Queue length

No major persisting queues were formed in any of the 3-1 contraflow scenarios.

Speed

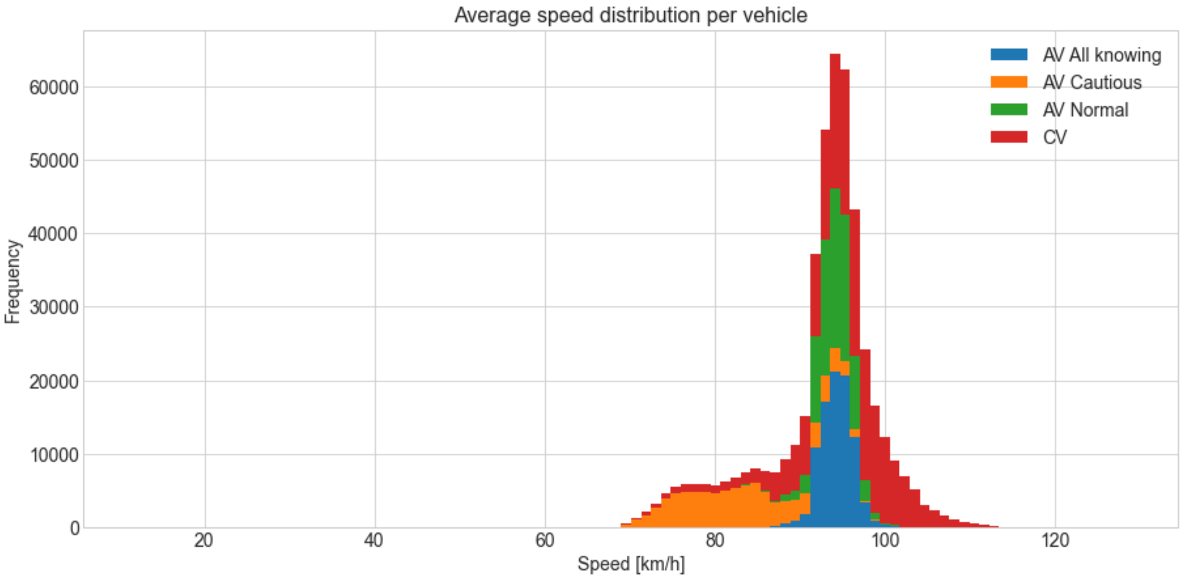


Figure D.2: Average driving speeds of different vehicle types on the road section right before the contraflow system

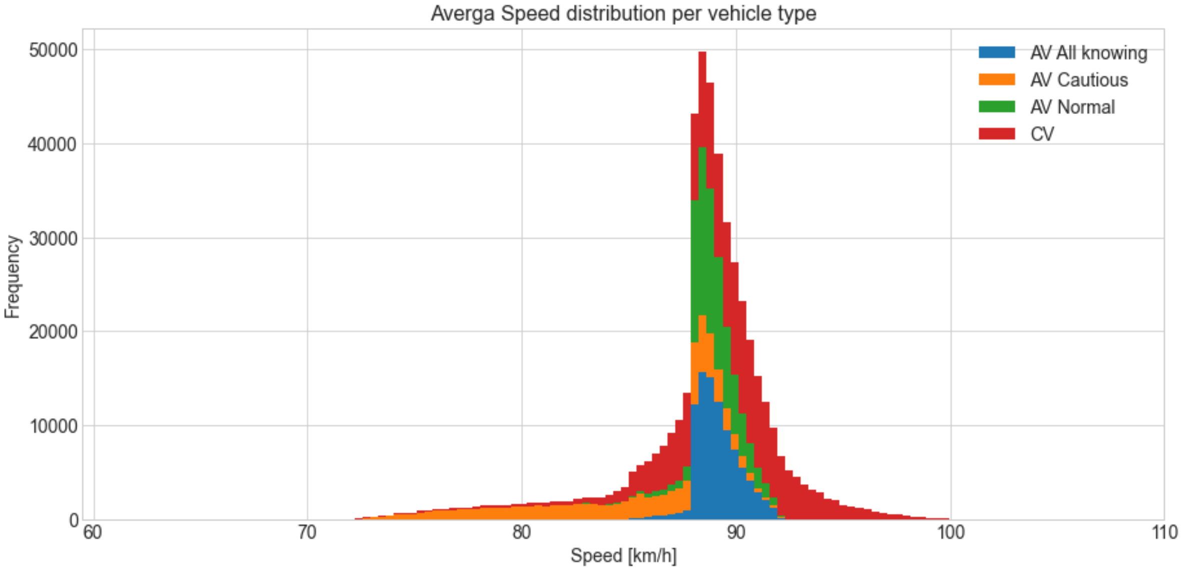
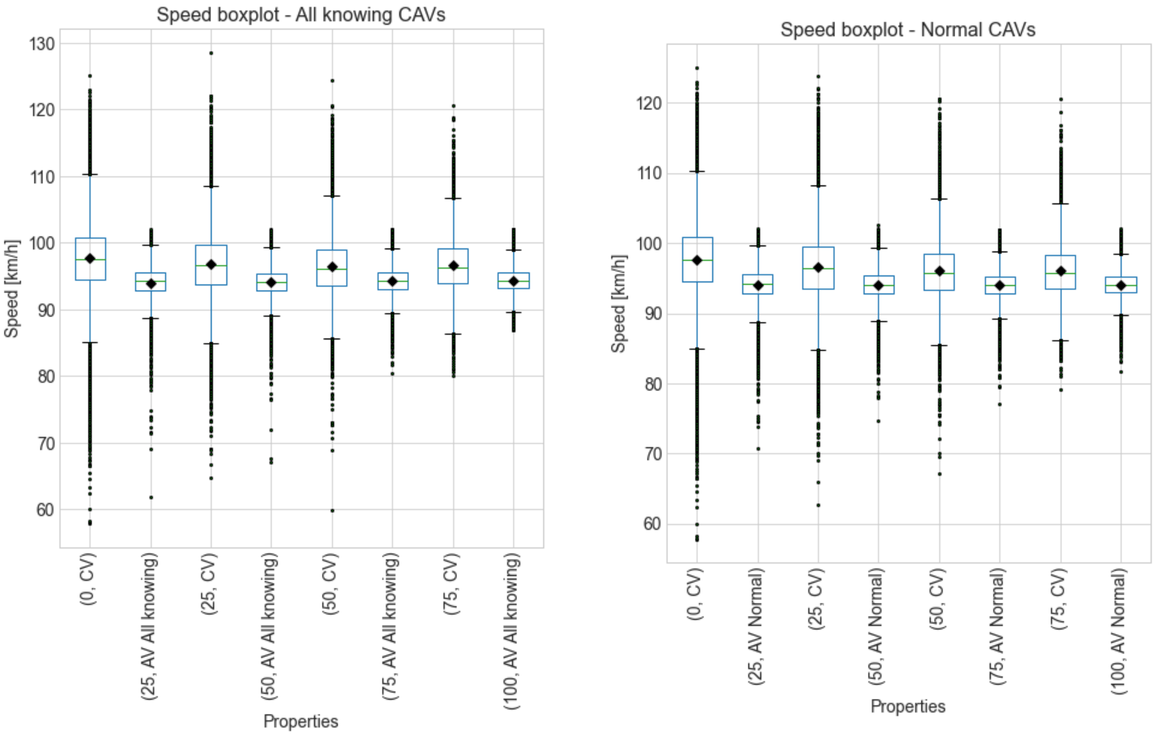
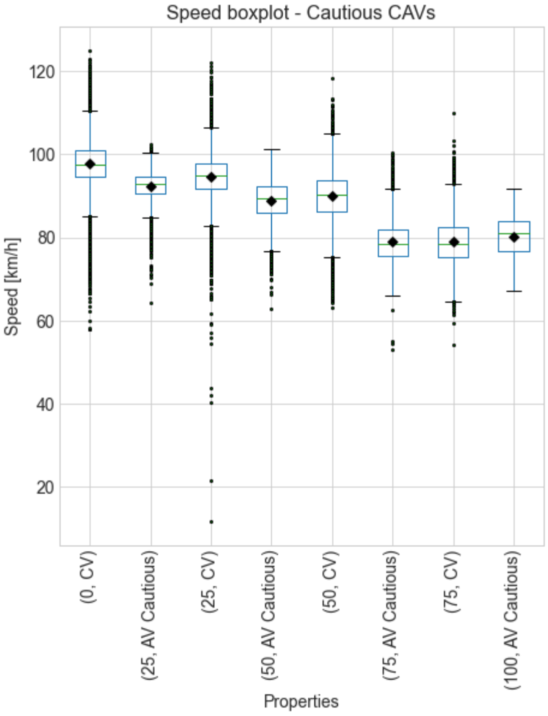


Figure D.3: Average driving speeds of different vehicle types on the road section within the contraflow system



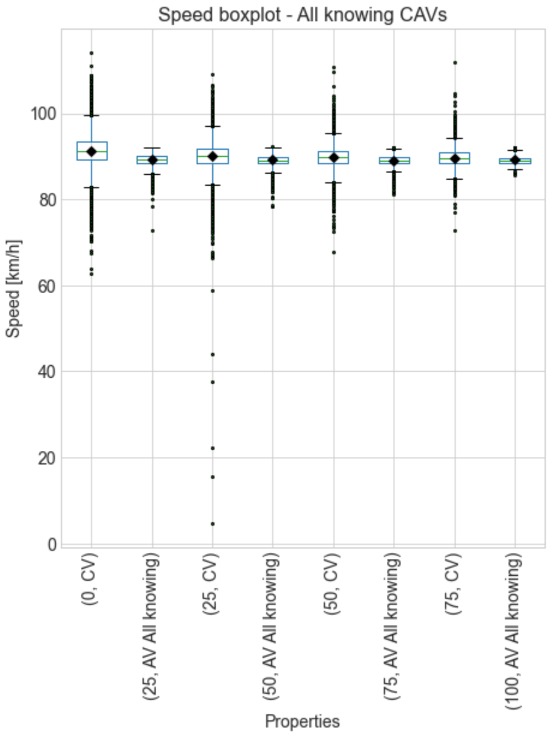
(a) All knowing CAVs and CVs

(b) Normal CAVs and CVs

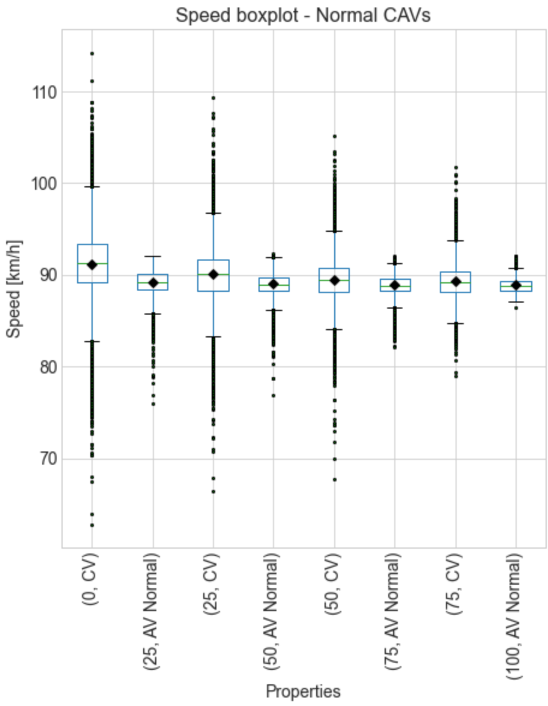


(c) Cautious CAVs and CVs

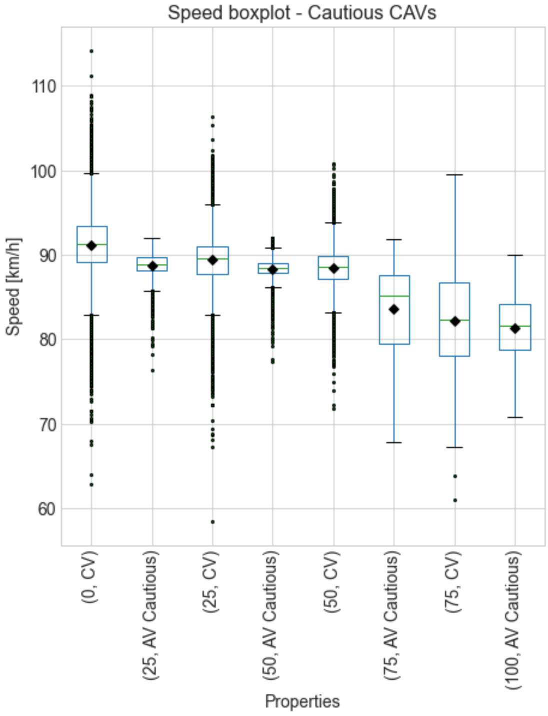
Figure D.4: Speed boxplots grouped by vehicle type and penetration rate on the road section right before the contraflow system



(a) All knowing CAVs and CVs



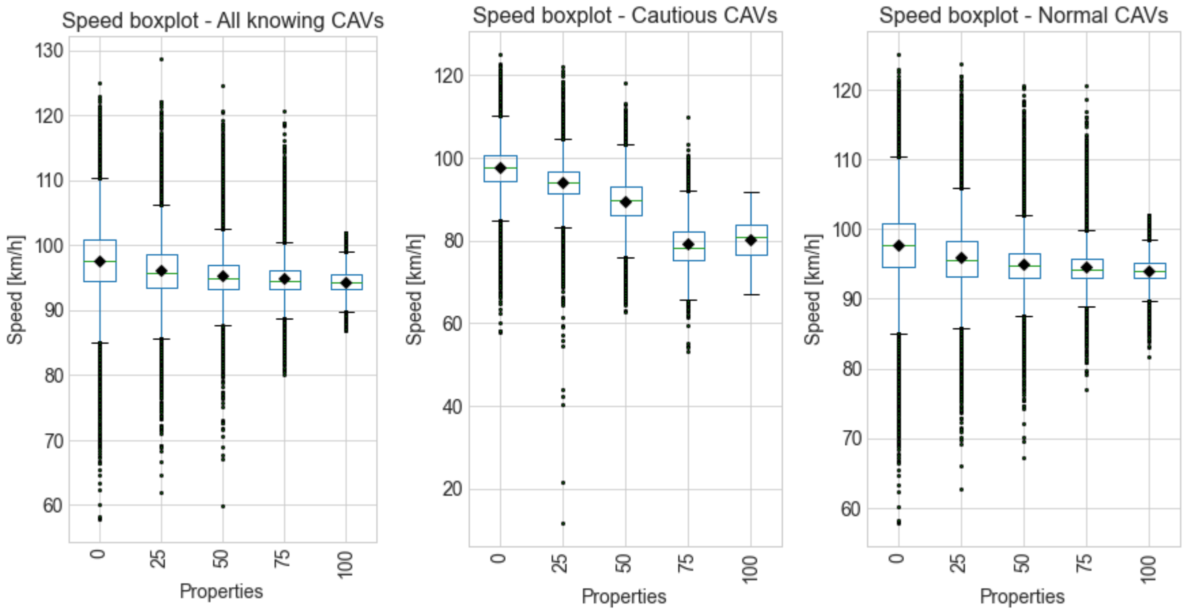
(b) Normal CAVs and CVs



(c) Cautious CAVs and CVs

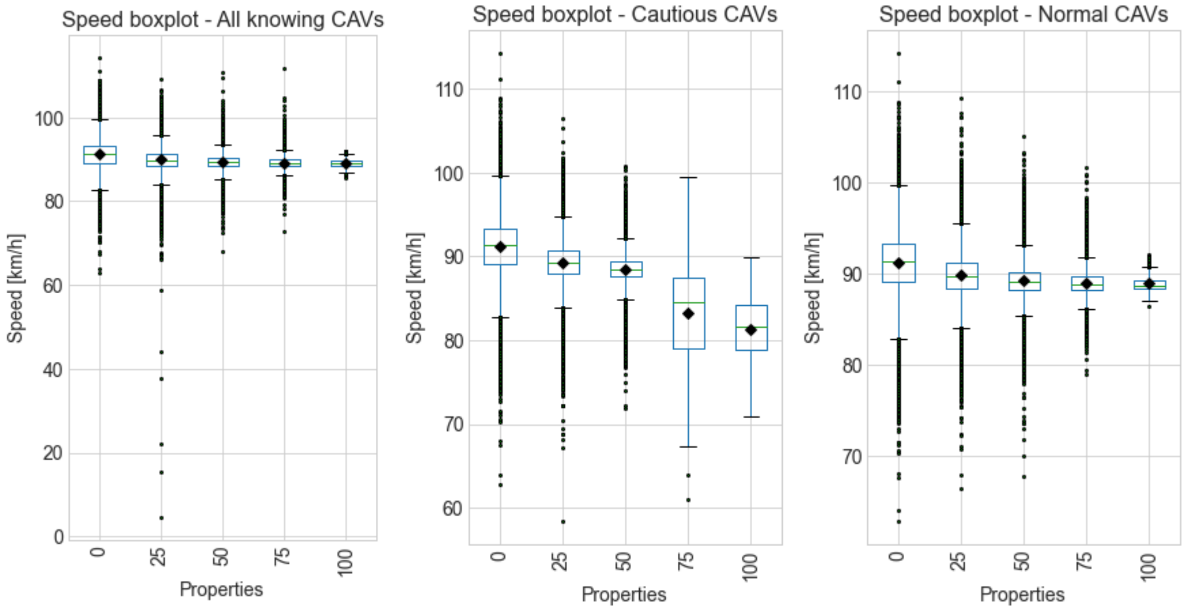
Figure D.5: Speed boxplots grouped by vehicle type and penetration rate on the road section within the contraflow system

Speed variability



(a) All knowing (b) Cautious (c) Normal

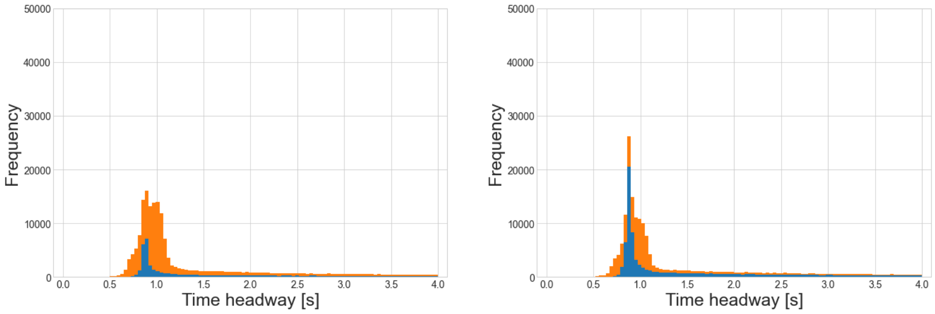
Figure D.6: Speed variability boxplots grouped by scenario on the road section right before the contraflow system



(a) All knowing (b) Cautious (c) Normal

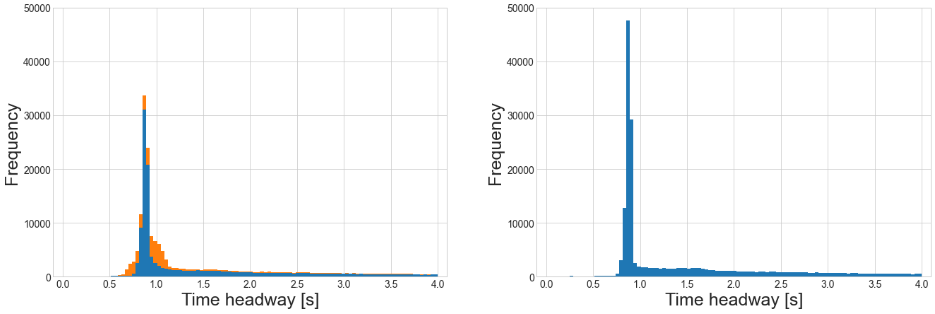
Figure D.7: Speed variability boxplots grouped by scenario on the road section within the contraflow system

Time headways



(a) 25% all knowing

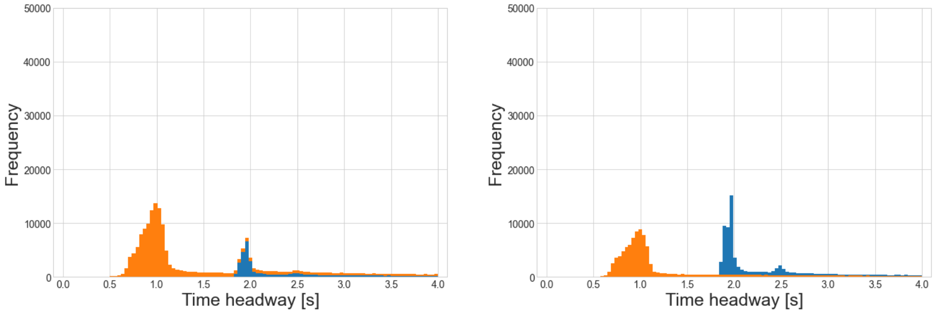
(b) 50% all knowing



(c) 75% all knowing

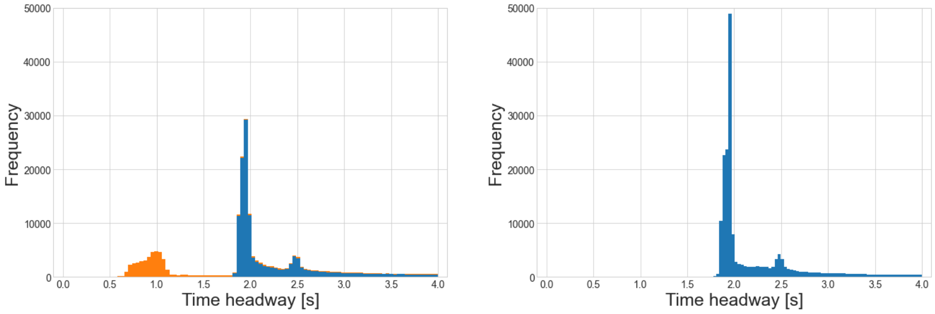
(d) 100% all knowing

Figure D.8: Frequency plot of simulated time headway observations at different penetration rates of all knowing CAVs (blue) in combination with conventional vehicles (orange)



(a) 25% all knowing

(b) 50% all knowing



(c) 75% all knowing

(d) 100% all knowing

Figure D.9: Frequency plot of simulated time headway observations at different penetration rates of cautious CAVs (blue) in combination with conventional vehicles (orange)

Lane changes

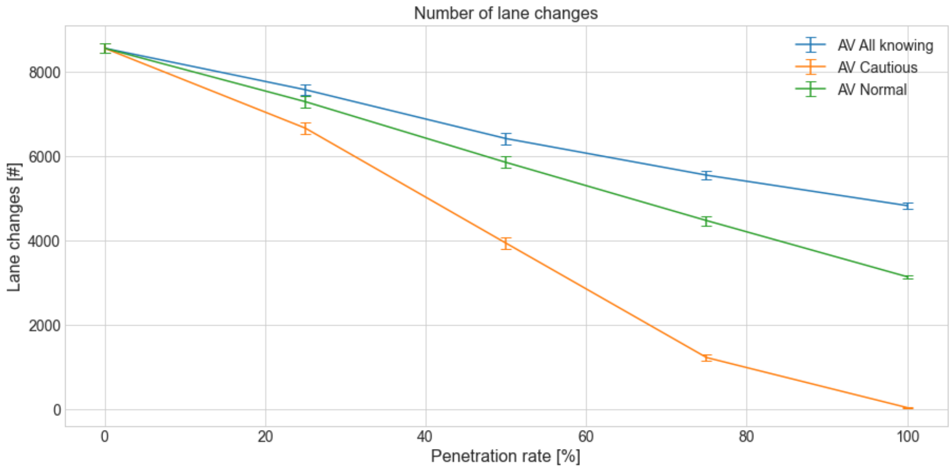


Figure D.10: Number of lane changes that take place on the entire road section before the work zone per scenario