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 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.

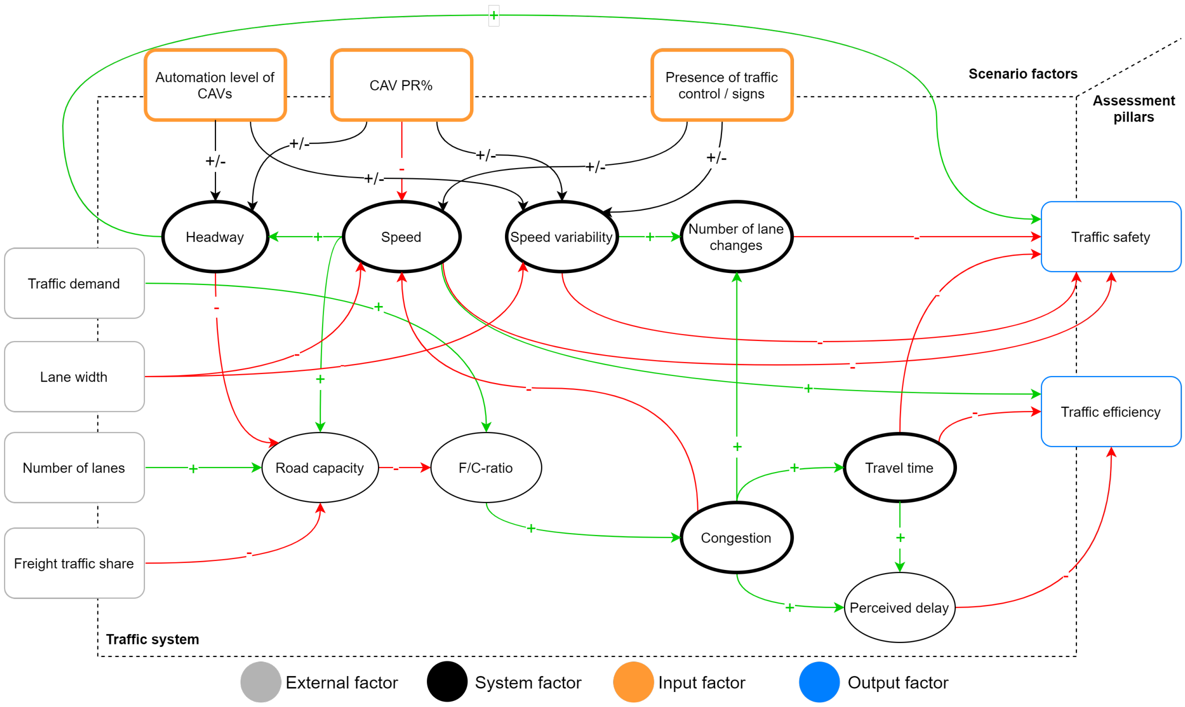


Figure 1: Causal diagram

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 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 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.

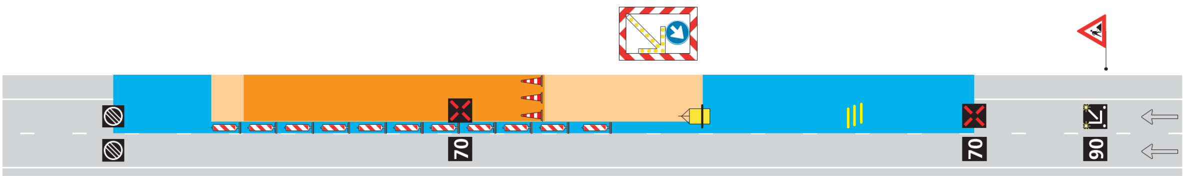
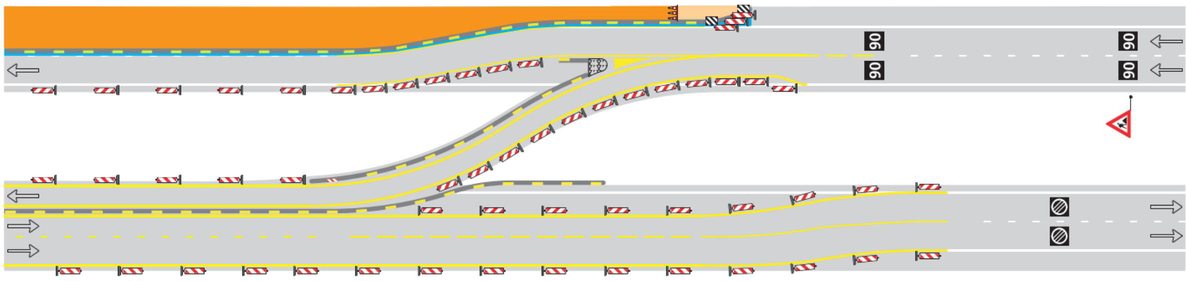
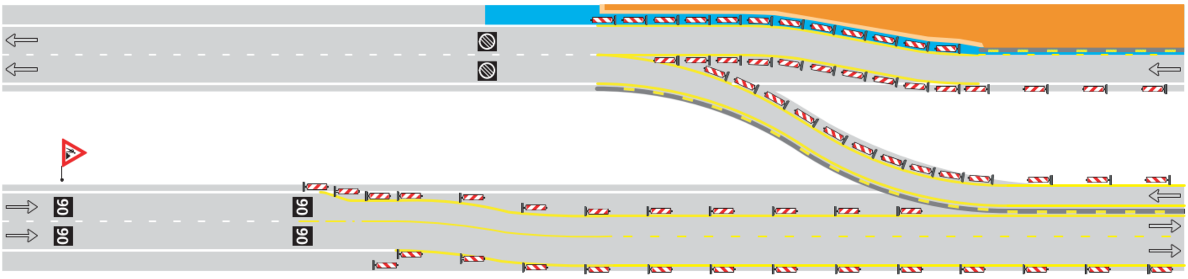


Figure 2: Right lane closure (CROW, 2020)

Figure 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 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 1.

Table 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 4. These 26 scenarios are all run 11 times.

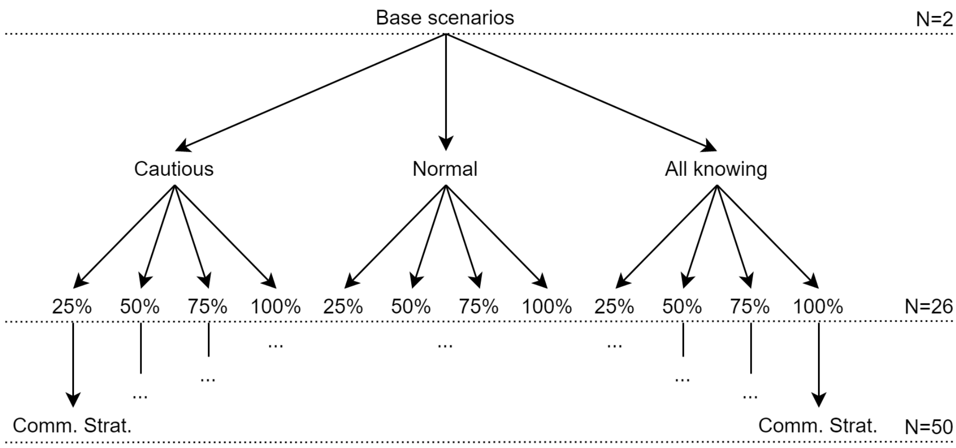


Figure 4: Scenario design

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

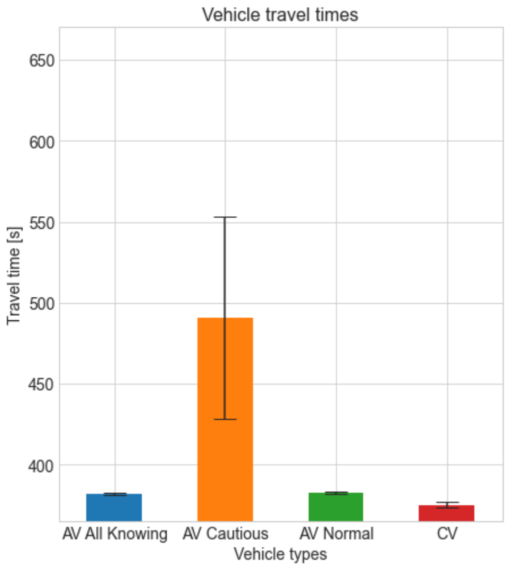
Based on the findings of the conceptual model, the KPIs were determined. The full list is presented in table 2. Travel time, queue length and average speed were used as KPIs for efficiency. Although these factors are related to each other, they were chosen to obtain a complete image of what the effects 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 2: Key performance indicators

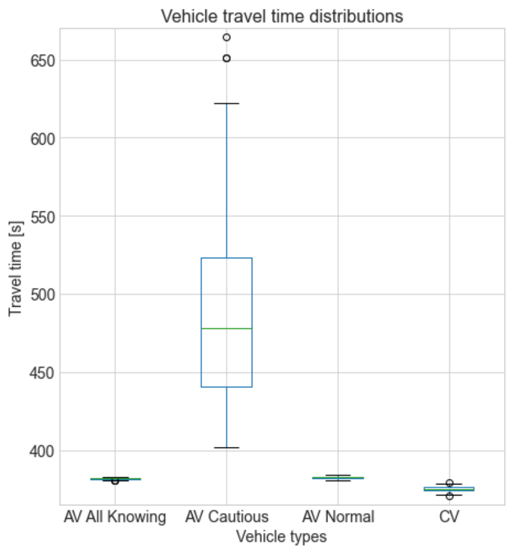
Traffic efficiency		**Traffic safety**	
KPI	**Unit**	**KPI**	**Unit**
Travel time	[sec]	Speed variability	[km/h]
Queue length	[m]	Time headways	[s]
Speed	[km/h]	Lane changes	[#]

4. Results

The traffic efficiency related findings showed that as the penetration rates of CAVs increased, the average travel times increased as well. Figure 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.



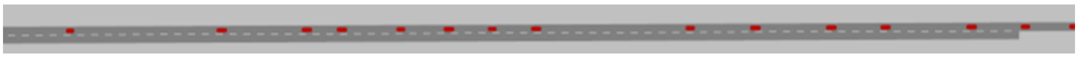
(a) Vehicle travel time averages with standard deviations



(b) Vehicle travel time distributions

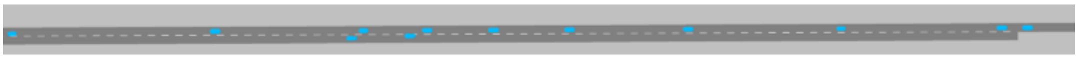
Figure 5: Vehicle travel times and distributions at 0% and 100% CAV penetration

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 6. The 3-1 contraflow simulations did not show any congestion for any of the scenarios, so no large travel time differences occurred there.

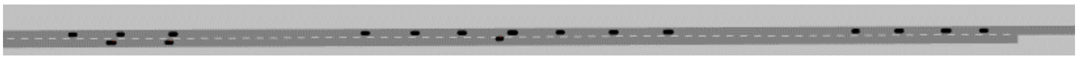


(a) 100% All knowing

(b) 100% Cautious



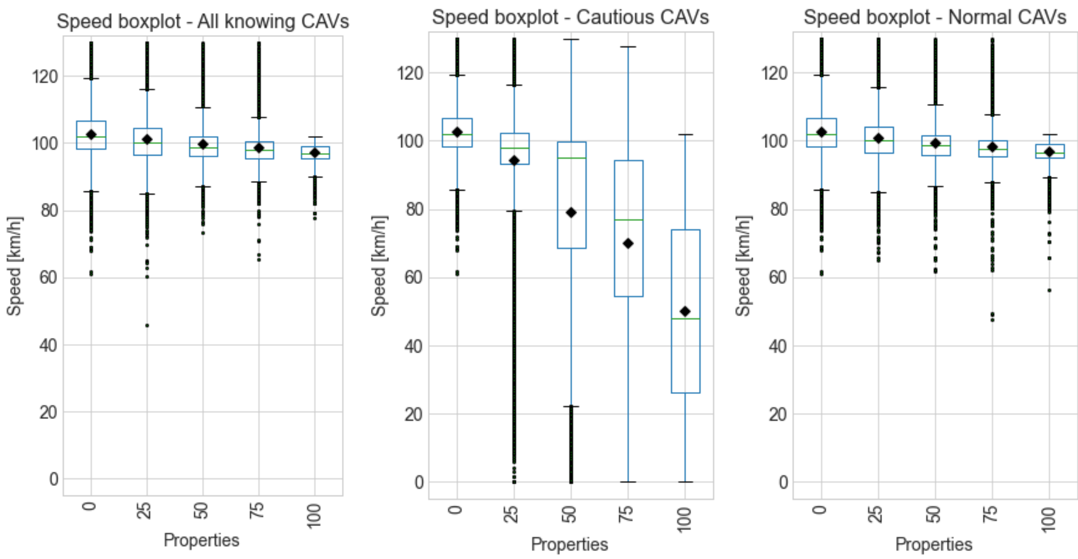
(c) 100% Normal



(d) Conventional vehicles

Figure 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 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

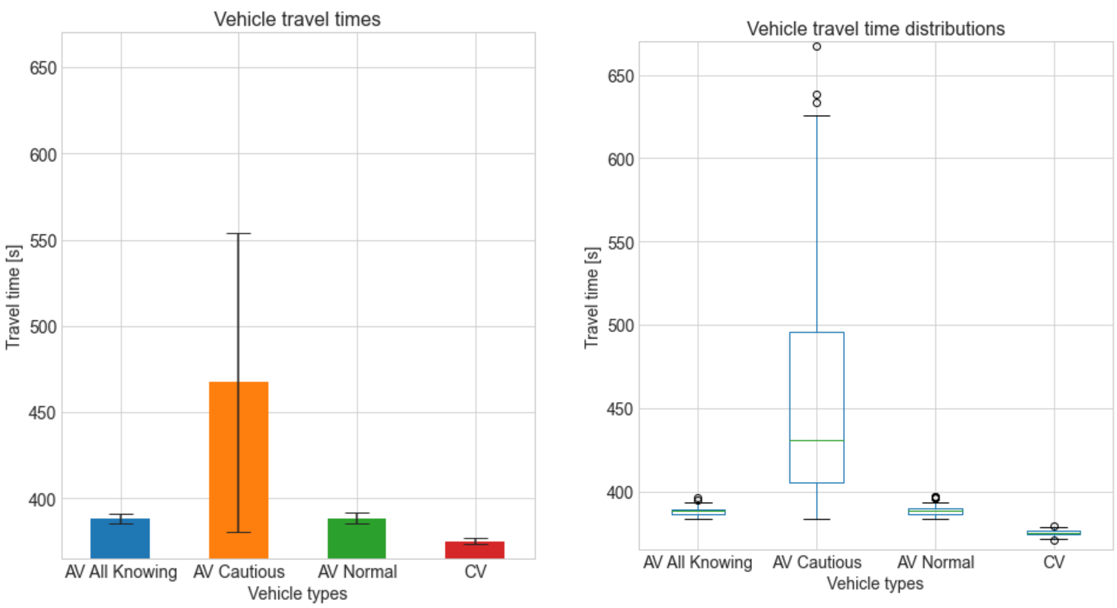
Figure 7: Speed variability boxplots grouped by scenario on the road section right before the right lane closure

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 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.

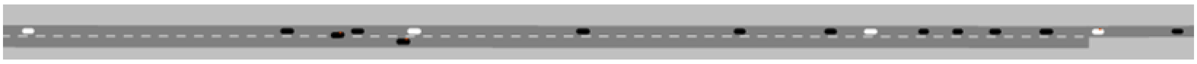
The implementation of the communication strategies affects the travel times in different magnitudes. The travel times and distributions per vehicle type are presented in figure 8. It was found that the average travel times in the cautious CAVs scenarios were reduced from 491 seconds to 468 seconds. The 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.



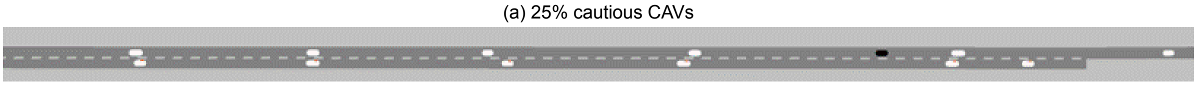
(a) Vehicle travel time averages

(b) Vehicle travel time distributions

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



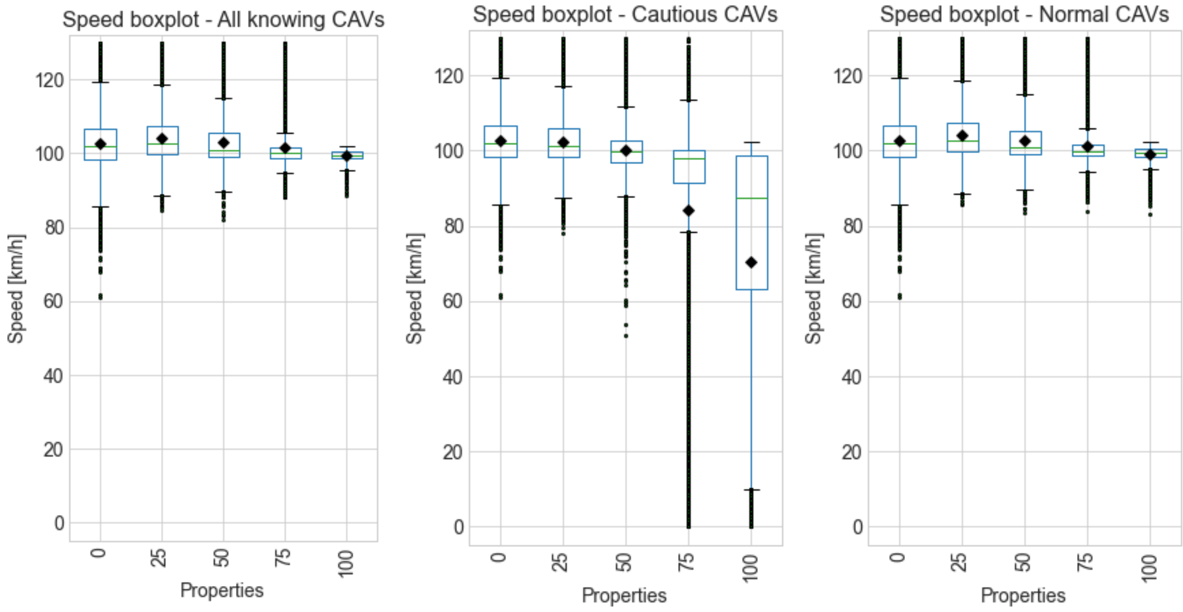
(a) 25% cautious CAVs



(b) 75% cautious CAVs

Figure 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 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 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 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.

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