Safety implications of the introduction of AVs on rural roads

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Abstract: With the increasing research of autonomous vehicles coming closer to introduction in society, it is necessary to research the effects on traffic safety for the introduction of these types of vehicles for rural roads. A lot of research has been done for the introduction of AVs on highway roads, researching the introduction for rural roads is the next step for the implementation of AVs in society. With this thesis the goal is to explore the traffic safety effects on rural roads with the help of agent-based modeling. An agent-based model was created to examine the effects of the penetration rate of AVs on traffic safety and how the characteristics of rural roads would affect traffic safety in this regard. Two main conclusions were drawn from the results. The first is that the introduction of AVs would lead to a lesser heterogeneity of speed between vehicles, this would in turn result in fewer casualties. The second conclusion is a conclusion drawn based on the emergent behavior of the model, the introduction of AVs would lead to less headway for AVs. Future research could be undertaken to study effects of overtakes on vehicle platoons.

Keywords: AVs, rural roads, agent-based modeling, overtaking, traffic safety

1. Introduction

The CBS (Central Bureau for Statistics) in the Netherlands, a Dutch independent government agency reported on the 15th of April 2020 that there were 661 casualties on Dutch roads in 2019 (CBS, 2019). The total number of casualties had decreased slightly from 2018 but the car as a transport mode has seen a slight increase in casualties. Something worth noting is that residents 60 years of age and up consist of more than half of the casualties. The cost of traffic deaths in the Netherlands (€12.5 billion) are higher than the environmental damages and traffic congestion (€9.1 billion) combined (Van Wee & Annema, 2009). The Dutch Minister Cora van Nieuwenhuizen leading the Ministry of Infrastructure and Water Management expressed on a press conference on the 11th of December 2019 that traffic safety must still be improved and that these casualties cause huge suffering and sadness on the people surrounding the victims (Rijksoverheid, 2019).

An innovation that can help to improve traffic safety is the autonomous vehicle (AV). A reported benefit of Autonomous Vehicles is improved traffic safety (Petrović et al., 2020). Autonomous Vehicles don't have the shortcomings of human drivers such as not obeying the law, driving too fast and not paying attention (Curbed, 2020). The Dutch police have seen a significant rise of drivers who do not obey the law and partake in deliberate dangerous driving behavior in recent years (RTL Nieuws, 2020). This behavior consists of driving on emergency lanes, tailgating, driving on blocked highway lanes, holding a phone in the car and more. The number of fines fitting this kind of behavior has risen 52% in 2019 in comparison with 2018 (RTL Nieuws, 2020). In the same article a Dutch professor named Bert van Wee of the Technical University of Delft described these actions as very dangerous and often a cause of accidents.

The scenario of AVs on Dutch roads is still quite far away as currently fully autonomous vehicles are not allowed to drive on Dutch roads yet as they legally require a driver (Wegenverkeerswet, 1994). Before this scenario will take place, a transition phase will have to occur with a mixed flow of autonomous and human-driven vehicles. But the challenge is not merely technical, it is also social. AVs will also have to communicate with human drivers as humans do not always follow the traffic rules. Driver behavior will have to be regulated and enforced from a government perspective. It is clear that the integration of autonomous vehicles on Dutch roads needs to be researched further as it can have a large effect on transport safety. In this master thesis this topic will be researched for the Netherlands.

Autonomous vehicles have been widely regarded to bring a number of benefits to the transport field. Among these benefits are: a dramatic reduction in traffic incidents, a reduced need for parking space, improved traffic efficiency, increased mobility for the elderly and opportunities for extra leisure time (Harper et al., 2016; Petrović et al., 2020; Van der Laan & Sadabadi, 2017). These benefits have been attributed to fully autonomous vehicles, however in the long term: an estimation is given of 2030 or even 2040 before these fully autonomous vehicles are expected to be ready to drive on the road in a fully autonomous mode (Except, 2016). Lavasani et al. (2016) expect a shorter timeline however where an implementation as soon as 2025 is mentioned. In Chan (2017) it is only expected that manufacturers would have their automated vehicles ready between 2020 to 2030 (Rataj, 2018). It can also be said that the introduction of the AV will rely on the technological developments of the manufacturers (Todorovic et al., 2017).

In literature there are two main visions on how AVs can be implemented together with human-driven vehicles (Todorovic et al., 2017). The first idea is that the autonomous vehicles are of low intelligence and the infrastructure is considered as smart to facilitate understanding between the two. The second vision is that the AVs are smart and the infrastructure is not. In that case the AVs are required to monitor other traffic and react to that traffic. The current trend of developing AVs follows the second vision where vehicles are highly intelligent and monitor nearby traffic. This research is already taking place on the roads in multiple states of the US (Favarò et al., 2018).

In Petrović et al. (2020) several other scientific papers are reviewed, across these studies it was found that AVs have been involved in more accidents than human-driven vehicles (HDVs) in percentage terms. They refer to Favarò et al. (2017) stating that the most occurring type of accidents with AVs is an accident where an HDV rear-ends an AV. This portrays a picture that the fault lies with the driver of the HDV, but it could also mean that the driver of the HDV is not used to the behavior of the AV.

A lot of research has been done on AV implementation on highways which are easier to comprehend for AVs as there is no crossing traffic. Rural roads have a larger variation of road users, greater variety in speeds of road users, have crossing traffic and often have the characteristic of overtaking on the opposite lane (Richter et al., 2017). Rural roads are the most dangerous roads per km in the Netherlands whereas highways are nearly the safest roads per km, only 30km/h roads cause less traffic deaths per km (Van Wee & Annema, 2009). It then makes sense to conclude that the greatest safety benefits the AV will contribute to are on rural roads, these typically have speeds of 60-90 km/h in the Netherlands. The main discrepancy in insight today is the safety implication of AVs for rural roads. It is not known how AVs will deal with overtaking of HDVs on rural roads or how the introduction of AVs will affect safety indicators for rural roads.

After this introductory chapter the decision rules, spacing of several vehicle types and the safety aspect on rural roads will be reviewed with a literature review in the second chapter. After that will be the methodology chapter, the results will then follow concluding with a discussion and conclusion.

2. Literature review

The implementation of autonomous vehicles will likely be a gradual change and it is also likely that AVs and HDVs will share the roads for an extended amount of time (Yao et al., 2020). It is known that the driving behavior of AVs can be written by programmers and the AVs will follow their programming. The HDVs display more diverse and random driving behavior than AVs and the driving behavior of HDVs is also more complicated to model than that of AVs (Yao et al., 2020). So HDVs will display more heterogeneous driving behavior and AVs more homogeneous behavior.

There have been several scientific papers measuring the penetration rate of AVs and their effects on road capacity such as in Mohajerpoor and Ramezani (2019), Ye and Yamamoto (2018) and Ghiasi et al. (2017). In these papers very mathematical models are used focusing on the spacing preferences of AVs. They depict that AVs will need shorter lead times to vehicles ahead. These papers also discuss the use of lane reallocations such as reserving a lane for AVs. In Dutch rural roads however this is often not possible as the majority of rural roads are 1-lane per heading so mixed traffic conditions will apply. In another study by Chen et al. (2017) road capacity with different penetration rates of AVs were calculated. These were done with some assumptions such as constant spacing preference by HDVs and AVs. This is not the case in real life as some drivers are happier with shorter lead times to vehicles in front than others.

In a research paper by Bose and Ioannou (2003) it was argued that the implementation of AVs could help stabilize traffic flow by flattening peaks such as aggressive behavior of drivers of HDVs. A less aggressive deceleration and acceleration of HDVs will resort in a more heterogeneous traffic flow, which in turn causes extra emissions (Adamidis et al., 2020). Talebpour and Mahmassani (2017) state that AVs are more capable than HDVs as they can have a better understanding of the surroundings in terms of traffic flow thereby making better decisions and making those decisions faster. Because of the wider view of surrounding traffic it makes the AV able to drive in a smoother driving style benefitting overall traffic flow.

Safe driving behavior can be characterized by an absence of negative variables such as fatalities and injuries (Lehtimäki, 2001). This is true but safe driving behavior can’t be solely defined with this description, positive indicators have to be mentioned as well. Among such positive indicators are sufficient headway, a short perception response time, adhering to the speed limit, calm driving, obeying traffic rules, planning ahead and paying attention to the road.

Unsafe driving behavior can be characterized by the use of drugs and alcohol, fatigue behind the wheel, a low attention span, anxiety of the driver, work-related tension, speeding, racing and other risk-taking behavior. A specific kind of unsafe driver behavior is the act of road rage. Road rage colloquially speaking is rude and unsafe driving behavior from one motorist directed specifically to other motorists partly or wholly caused by frustration of the first motorist. James & Nahl (2000) further specify 3 components of road rage. The first component is the vocal aggression of the motorist directed at the other(s). The second is intimidating the other motorist with the use of the own vehicle either by attempting to make contact or directly threatening the use of the vehicle to make contact with the other motorist. The third and final is physical contact with the vehicle or either stepping outside of the vehicle to further argue with the other motorist.

One specific maneuver which has led to several collisions in the past on rural road is the overtake. Head-on collisions have caused the most significant number of deaths on rural roads (Figueira & Larocca, 2020). In Zheng (2014) the author explains two kinds of reasoning for overtaking. One is called the mandatory overtake which relates to overtaking to reach the destination in time. The second is the discretionary overtake which can be further categorized into two categories. The first is to acquire a higher speed than the vehicle in front and the second is to acquire a better position on the road. This position on the road could be a position with less traffic, a position with more oversight in relation to other traffic or even a better scenery. Although the paper of Zheng (2014) relates to highway conditions the motives for overtaking will not be different for rural roads as both motives can also apply for rural roads.

Congestion is a complicating factor for overtaking. When overtaking the driver has to perceive the gap to the vehicle in front, the gap in front of the vehicle in front, the speed of the vehicle in front, the gap on the other lane and the speed of the vehicle on the other lane especially if the other lane has a heading in the opposite direction. In order to achieve a successful overtake at least 2 conditions stipulate a sufficient gap on a lane namely the gap in front of the vehicle in front and the gap on the other lane. In heavier traffic conditions in terms of traffic flow these gaps will be shorter on average. Wilson & Best (1982) found in quite an old study that 14% of drivers on a British carriageway performed an overtaking action in which the gap was not sufficient for a comfortable overtake.

There are generally two overtaking strategies used in overtaking maneuvers, namely the flying and the accelerating maneuver as described by Hassan et al. (2014). The flying maneuver is a strategy whereby the vehicle does not decelerate before overtaking but continues on with a constant higher speed than the vehicle in front. The accelerating overtake is an overtake whereby the overtaking vehicle first matches the speed of the vehicle in front, then moves to the side and accelerates past the vehicle originally in front. Intuitively the accelerating overtake will cost more time and therefore more distance will have passed.

A characteristic of overtaking on two-lane rural roads is that the lane in which the overtaking vehicle has to pass the vehicle in front is actually meant for vehicles in the opposite direction. This also makes the consequences for a failed overtake more grave than on highway roads. When both speed limits and overtaking restrictions are legislated, are rural roads at their safest (Richter et al., 2017).

Summarizing this literature review it can be stated that safe driving behavior of HDVs is characterized by vehicles which adhere to the speed limit with sufficient headway and where drivers are driving in a good physical condition. Frustration of drivers of HDVs can lead to unsafe driving behavior. Overtaking is especially dangerous on rural roads due to the characteristic of head-on traffic on the opposite lane. This characteristic is not present on highway roads. A flying overtake is deemed safer than an accelerative overtake.

3. Methodology

The contextual framework of the 10-step process by Van Dam et al. (2012) was used as a blueprint for this study in order to guide the ABM oriented research. It was used because it can analyze large scale socio-technical complex systems with the help of agent-based modeling. This approach consists of the following 10-steps:

1. Problem formulation
2. System identification and decomposition
3. Concept formalization
4. Model formalization
5. Software implementation
6. Model verification
7. Experimentation
8. Data-analysis
9. Model validation
10. Model use

The steps of 1-5 will not be described per step but only shortly, there will be a larger focus on the results, discussion and conclusion because a scientific paper is traditionally more concise.

Why ABM

Agent Based Modeling (ABM) can be used in traffic safety models that show emergent behavior with agent-level decision rules as they move around the confined space that is programmed in a model (Kagho et al., 2020). ABM can capture the behavior of an individual agent and its interaction with the environment (Le Pira et al., 2017; Gilbert, 2008). Agent-based models also have the benefit that they are easy to graphically display.

ABM is a great modeling tool but it also has some disadvantages. Assumptions and data can for example introduce error into the model (Kagho et al., 2020). Another is that ABM focuses on predicting future scenario's while there are actually few validated predictions of ABM (Kagho et al., 2020). However the focus here lies on understanding the behavior of the model, gaining insight and basing policy decisions upon that.

Agent-based modeling is suitable for a complex system if there are three requirements met as described by Van Dam (2009). The first is that each agent is somewhat autonomous in its behavior. The second is that the agents in the system interact in a very dynamic system. The third and last requirement is that subsystem interaction is very flexible (Van Dam, 2009). In this case all 3 conditions are met. Each agent is an HDV or an AV and is autonomous in its behavior. Traffic is also highly dynamic and the road users follow the rules of the road and interact with each other on a subsystem level with different actors in their vicinity.

Problem situation

The problem situation has already been thoroughly described in the introduction so it will only be summarized shortly. The main problem is that there is a lack of insight on how the transition phase of going from HDVs to AVs will impact the traffic safety on rural roads. The initial hypothesis is that Autonomous Vehicles in regards to human-driven vehicles will display safer traffic behavior and that this will lead to less accidents and therefore less traffic deaths.

Input data

Input data for the agent-based model such as speeds on rural roads were taken from scientific literature or governmental organizations. The data was used for an agent-based model programmed in Netlogo. The data was analyzed and graphically depicted with RStudio in order to make conclusions about the data.

First, all of the input parameters have to be set for the model. In order to make a realistic simulation input parameters are reviewed. For instance the number of trucks which has to be set. Trucks have accounted for 5,5% of all driven vehicle kilometers on Dutch roads in 2019 (CBS, 2020). Conventional cars have accounted for the majority of driven vehicle kilometers in that same year with 80,1% of all driven kilometers (CBS, 2020). That means that the ratio of truck to HDV should realistically be 1:14,5, but with the small scale of the model it is presumed that the number of trucks should be set to 1 truck for each model run and to let the number of AVs and HDVs vary based on the hypothesis.

The number of runs is set to 50 for each simulation as different model runs could be very path dependent based on which vehicles are created on either the top or bottom lane and the heterogeneity of speeds of HDVs. A time limit is set of 1000 ticks in order for the model runs to converge.

Output

The output data which are most important are derived from the literature study. These are the headways for the vehicle types, the amount of injuries and the amount of casualties. Because drawing the line between an injury and a death is an arbitrary modeling choice by the modeler a simplification has been made that when two vehicles collide, it will always result in a death for both vehicles.

Verification

The model code has been programmed on a step-by-step basis where functions were only added after previous functions were completed. This helped to determine how the implementation of new functions led to problems with the old programming code. A technique which was frequently used was the technique 'recording and tracking agent behavior' as described by Van Dam et al. (2012). The model was simulated several times at low speed with the help of tracking the agent to solve unwanted behavior. A flaw in the model was corrected where agents drove backwards, the agents are only expected to drive forwards.

A difficult property to model and to make agents behave correctly was to model the headway of an agent. As the world of the model has negative x-coordinates a normal subtraction formula would not work as headway would become either a large negative number for the case of agents with a heading of 90 (facing east) or very large for a vehicle with a heading of 270 (facing west).

Validation

The chosen method to validate the model is through a literature validation, a similar result of the model outcome compared to literature increases the reliance of the model results. Other validation methods such as expert validation can be used but it is chosen not to use those methods due to the scope and the timeframe of this thesis. Interviews or workshop groups with numerous experts can be time consuming. Validation by model replication is also not used because of the time constraint.

General conclusions of several research papers are in line with model behavior. In the study of Ivanco (2017) the headway of autonomous vehicles is analyzed in time instead of distance, this does not affect results too much as time can also be converted to distance with speed. The headway of AVs in the study of Ivanco (2017) in figure 1 resembles that of the headway of AVs in the created Netlogo model in figure 2. Because these model characteristics show similar behavior, the model is assumed to be validated, although partially

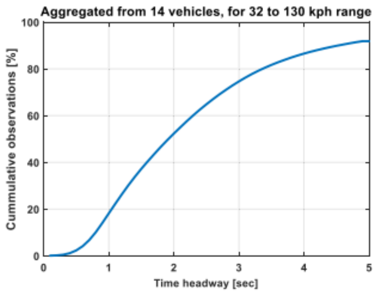

Figure 1: Headway of vehicles (Ivanco, 2017)

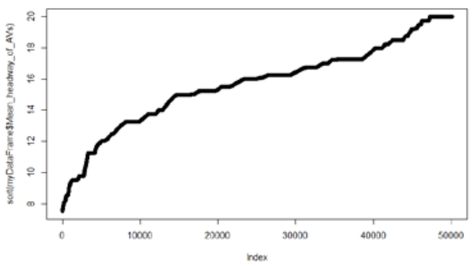

Figure 2: Headway of AVs from a model run

In a scientific paper by Micó et al. (2018) driving techniques are compared between a distance-oriented approach and a inertia-oriented approach.

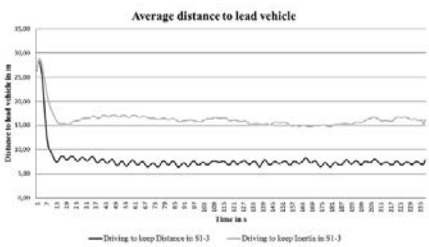

Figure 3: Headway HDVs (Micó et al., 2018)

Figure 3 shows two lines, the bottom darker line is for the distance-based approach and the lighter line is for the inertia-based approach.

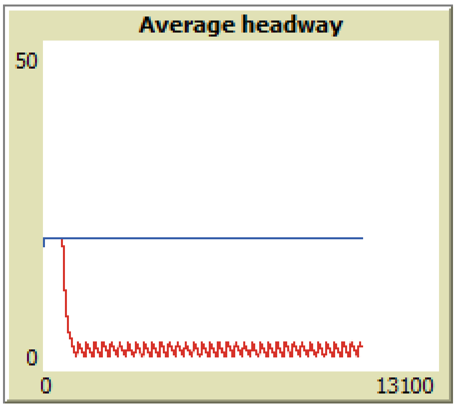

Figure 4: Headway of HDVs from model (red)

The distance-based approach closely resembles the behavior of a Netlogo model run in figure 4 where HDVs drive toward a truck and are stuck behind it, they will not attempt to overtake the overtaking conditions have not been fulfilled. The headway of the HDVs oscillate as their acceleration characteristics are based on distance. These patterns coincide with one another.

Because these two model characteristics show similar behavior, the model is assumed to be validated, although partially. In the next section the model is tested to what it is sensitive to.

Finally a screenshot is shown of the used model in figure 5 which can make the model more clear.

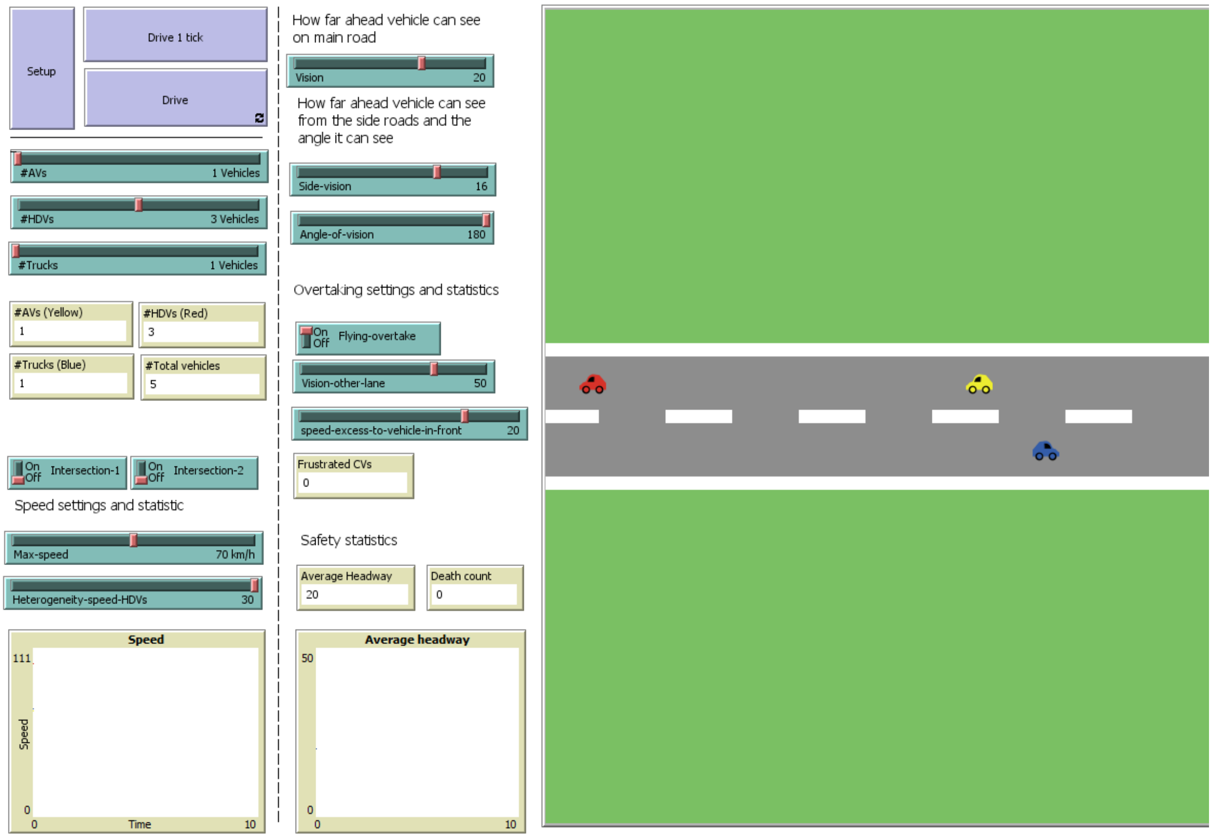

Figure 5: Screenshot of the user-interface of the Netlogo model

4. Results

There are two hypotheses which are to be tested with the agent-based model.

Simulation 1

The first hypothesis is that the influence of a more heterogeneous traffic flow will affect traffic safety negatively on Dutch rural roads. AVs could help reduce traffic flow stochasticity and thereby mitigate speed heterogeneity. These attributed effects of AVs can also be modeled for HDVs as their base programming is the same in the Netlogo model minus the overtaking.

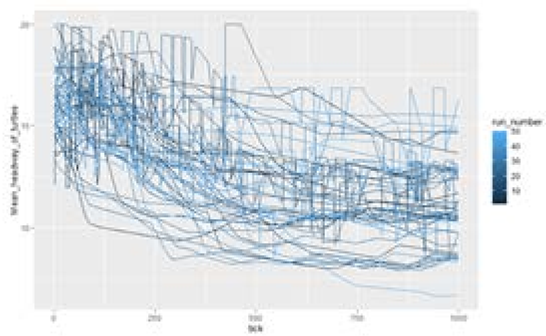

Figure 6: Plot of model runs - mean headway simulation 1, experiment 1

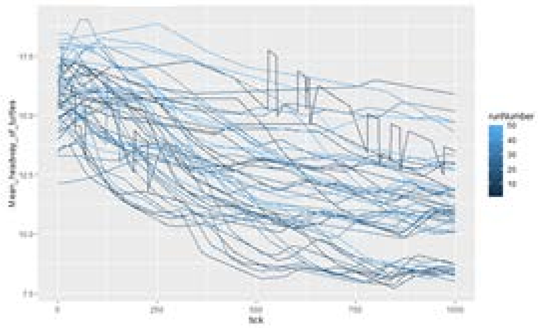

Figure 7: Plot of model runs - mean headway simulation 1, experiment 2

The colored plots of model runs do show differences in model behavior for the model runs. It can be seen in figure 6 that the mean headways have more diffuse and irregular behavior than figure 7. This is the cause of less overtakes being carried out, after each overtake comes a rise in mean headway. The mean headways of vehicles are given for each of the 50 model runs in figure 6 and 7. Figure 6 with the experiment of a lesser heterogeneity of speed among vehicles has over a 100 bumps in the lines of headway for a model run denoting overtakes. Figure 7 displaying the results of the second experiment has fewer than 10 of such overtakes. This is in turn logical as the second experiment allows for less overtaking. In the first experiment the speed of HDVs can range anywhere from 30-90km/h as speed heterogeneity is set at 30. With the threshold to overtake at 25, several combinations can be made where an HDV can overtake another HDV or an AV which is programmed to adhere to the speed limit. In the second experiment the speed of HDVs can range anywhere from 45-75km/h, in this experiment there are ample opportunities for HDVs to overtake with the speed threshold in order to overtake at 25. There has to be a model run in which there would have to be 2 HDVs on the same lane with a difference in actual speed of 25. In figure 7 it can be seen this happens in 2 of the 50 model runs. It is concluded that the death count decreases with a decrease in speed heterogeneity of HDVs.

Simulation 2

The prediction is that an increased percentage of AVs will cause a smaller average headway. A smaller headway is stated as a safety indicator in traditional traffic safety literature, but with the introduction of AVs this can differ.

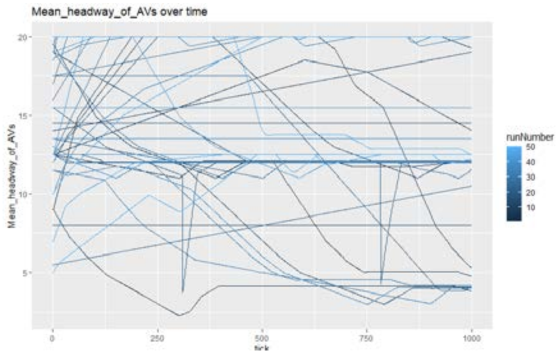

Figure 8: Plot of model runs - mean headway simulation 2, experiment 1

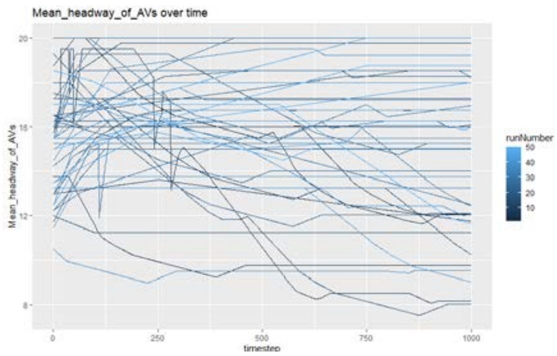

Figure 9: Plot of model runs - mean headway simulation 2, experiment 2

The plots of model runs in figure 9 show less heterogeneous headways than in figure 8, this is because the HDVs actually cause the heterogeneity and there are less of them in the second experiment so this is plausible. The peaks and drops are caused by overtaking maneuvers of HDVs.

The mean headway of AVs does increase with a higher percentage of AVs instead of HDVs. This is because AVs all have the same programmed speed and do not drive towards one another to form platoons but keep their distances based upon where they are created. In real life this would mean that wherever the AVs join the rural road they will keep that relative distance to other AVs if they also have the same speed, which is assumed they will have. It might be contradictory that AVs despite having the potential to follow with a shorter headway actually have a larger headway with an increased percentage of AVs.

Patterns do emerge in the model. It is shown that model runs are very path dependent. They are dependent on the number of vehicles created and in which lane they are set in. The vehicles to be created can be set but the lane which they are placed on is random in the models.

5. Conclusion

Two main conclusions can be drawn from the previous chapter. The first is that reducing the speed heterogeneity of HDVs will cause a decrease in the number of deaths. This heterogeneity works both ways: HDVs can drive either slower or faster than the speed limit determined by a uniform distribution. The second conclusion is that an increased percentage of AVs in everyday traffic will cause AVs to have more headway. With the current parameters of the model, with AV speed set equal for each AV in the model run, only HDVs will cause grouping behavior or platooning.

Based on the research in this thesis, it can be concluded that the speed heterogeneity of all vehicles will be lower and thus safer with the implementation of autonomous vehicles. Also this will help to reduce overtake maneuvers on rural roads. Overtakes are the main cause of head-on accidents on rural roads (Figueira & Larocca, 2020). The second conclusion is that a higher percentage of AVs will cause a greater average headway for AVs on rural roads as vehicles speed will be more consistent with more AVs. Headway is deemed to be a traditional safety indicator but this does not need to be the case for AVs.

Recommendations

The first conclusion that reducing the speed heterogeneity of HDVs will cause a decrease in the number of deaths on Dutch rural roads, this reduced speed heterogeneity will need to be enforced. Road authorities which are responsible for the rural roads can request additional enforcement of speed by law enforcement in order for a more homogeneous traffic flow. This can very likely only be done for enforcement of speed excesses and not for drivers of HDVs who drive too slow.

The implementation of AVs also have a side effect of reducing the number of overtakes on rural roads. Because a certain speed discrepancy is needed in order for an HDV to attempt an overtake these attempts will be less frequent. This is due to the fact that HDVs will encounter less vehicles on rural roads who do not follow the speed limit if there are more AVs. In order for traffic safety for rural roads to increase two main actions are advised. First enforcing the speed limit on rural roads and secondly encouraging the implementation of AVs.

Ethical considerations are also necessary for the transition phase of HDVs to AVs. It is assumed in chapter 4 that AVs will not overtake, this will be the safest option for a smooth implementation of AVs on Dutch rural roads. If in a later stage AVs would to overtake it would add the ethical and moral dilemma of how much risk to take during an overtaking maneuver. The moral dilemma would be the trade-off between the time gained by performing the overtake and the risk of ending up in an accident or a fatal one at that. This taboo trade-off between time gain (which could be measured in euros with the value of time approach) and human accidents or fatalities is immoral.

Recommendations are to ban overtaking by AVs during the transition phase from HDVs to AVs.

6. Discussion

This thesis has helped overcome the knowledge gap regarding the safety effects of the transition phase from HDVs to AVs on Dutch rural roads. The main links are that an increase in the percentage of AVs as part of the total number of vehicles will make rural roads safer. Also it has shown that the headway of an AV in the early stages of the transition phase might even become larger instead of smaller. This can contribute to the implementation of AVs on Dutch roads after it has been allowed for highway roads. The implementation of AVs on rural roads is the second step in the implementation of AVs on Dutch roads overall. Filling this knowledge gap is important because rural roads have a specific characteristic of head-on accidents which are not seen on highway roads.

Analysis

The first finding that this study offers is that with the introduction of AVs the speed heterogeneity of vehicles would be lower and this will cause safer travelling on Dutch rural roads by transport vehicles. One could say that the introduction of AVs alone would lead to less heterogeneity of speed, why does a model have to be created in order to prove this? Theory and practice do not always match, especially in an environment with many actors such as in this case the drivers on the rural road. Emergent behavior could arise which could result in unexpected behavior, this was not the case however.

The second finding of more AVs leading to an increased average headway for AVs is rather unexpected and exactly the type of emergent behavior which could come up in an agent-based model which could not arise in equation modeling. This finding is mainly due to the fact that each AV is programmed to maintain exactly the allowed speed on a certain road. The increased headway of AVs is partly caused by the behavior of HDVs. These would often become stuck behind AVs, as AVs would drive fast enough to not tempt HDVs to overtake but often slower than HDVs which would make them frustrated.

Limitations

The two greatest weaknesses of the current modeling method are validation issues and assumptions. Validation is done for a scenario which is not present in the real world yet. So only subsystems and smaller mechanisms can be validated but not the overall behavior of the model. Another validation issue is that only a partial literature validation has been done because of the scope and especially the timescale of the study, in order to make the research more legitimate expert validations could be done with a larger time frame.

There are two main bases on which this research can be made more realistic. In the current model a driver of an HDV only executes an overtaking maneuver if it thinks it can successfully overtake one vehicle in front. Additionally if an HDV could in fact overtake two or multiple vehicles in front of it, this would make the model more realistic as these situations do occur in the real world. It was not added due to the complexity of the model, it already cost considerable programming resources to implement the overtake of only one vehicle in the model. A second similar simplification is that HDVs are programmed not to overtake for an intersection but this also happens in the real world, but this would also make the model more complex and could be arbitrary when an HDV should overtake when there is an intersection in sight.

Future directions
The model could be made more realistic by making the world larger, then it would be easier to identify the effects of intersections on overtaking by drivers of HDVs. In the current model the behavior of agents was often not to perform an overtake as an intersection was always relatively nearby because the model was so small. So the added effect of an intersection was relatively small and offered no real insight with regards to overtaking before an intersection.

Future studies could focus more on the overtaking of HDVs on rural roads in a case where multiple vehicles are overtaken. With increasing penetration rates of AVs on rural roads it is likely that AVs could form platoons with other AVs or non-AVs. Studying overtakes of multiple vehicles by HDVs could lead to new insights on how dangerous or safe these types of overtakes are.

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