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Safety implications of the introduction of Autonomous Vehicles on rural roads

An agent-based modeling approach

(Collier, 2018)

Joey Brouwer
4164237
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Safety implications of the introduction of Autonomous Vehicles on rural roads

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Joey Brouwer

Student number: 4164237

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Graduation committee

Chair:	Dr. M.E. Warnier, Multi-Actor Systems
Second Supervisor:	Dr. J.A. Annema, Transport and Logistics

Executive Summary

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 has 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).

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). 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.

The implementation of AVs for Dutch rural roads is set to be researched for AVs who adapt to the infrastructure, not for AVs who communicate with the infrastructure. It is clear there is a knowledge gap on how drivers of Human-Driven Vehicles (HDVs) will react on the increasing penetration rate of AVs in the future on Dutch rural roads. This results in the next main research question:

What are the effects of the transition phase from HDVs to AVs in the Netherlands for traffic safety on rural roads?

In order to research this question an agent-based modeling (ABM) approach is used. Agent-based models can be used for traffic safety models that show emergent behavior with agent-level decision rules (Kagho et al., 2020). Safety indicators are first explored with a literature study. After that he 10-step process of using agent-based models by Van Dam et al. (2012) is used as a blueprint. The model is formalized, verified and validated in order to generate model results with the agent-based model runs via Rstudio programming software in combination with Netlogo. A literature validation is used where the outcomes of the model resemble existing literature.

The main safety indicators resulting from the literature review are headways for vehicles and safety statistics such as accidents and casualties. The driving behavior of drivers is stated to be more random and complex than the driving behavior of autonomous vehicles, autonomous vehicles do not overtake whereas drivers of human-driven vehicles do. For the results, two main simulations were performed. Firstly a simulation with two experiments where the heterogeneity of speed of HDVs was varied. The introduction of AVs will cause a drop in speed heterogeneity similar to this. The following plots show the average headway of all vehicles in the model run over a 1000 time steps for 50 model runs which are depicted with the lines in the graph.

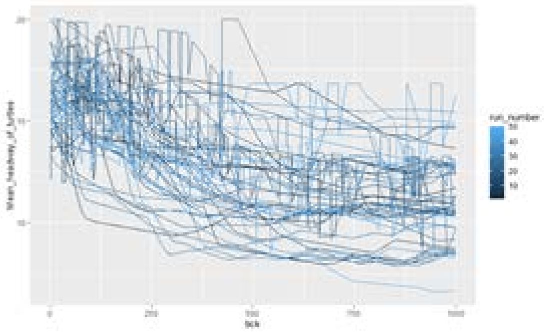

Figure A: Plot of simulation 1 model runs - mean headway experiment 1

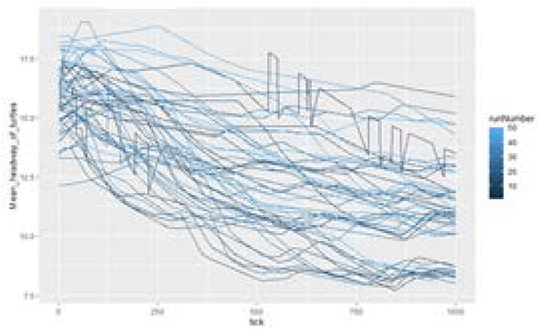

Figure B: Plot of simulation 1 model runs - mean headway experiment 2

It can be concluded that reducing the speed heterogeneity of HDVs will cause a decrease in the number of overtakes. In figure A in the experiment with a high heterogeneity of speed, several overtakes are performed (the sudden drops in headway for a model run) whereas these are less frequent in the second experiment in figure B for a lower heterogeneity of speed. This also caused for the amount of casualties to decline.

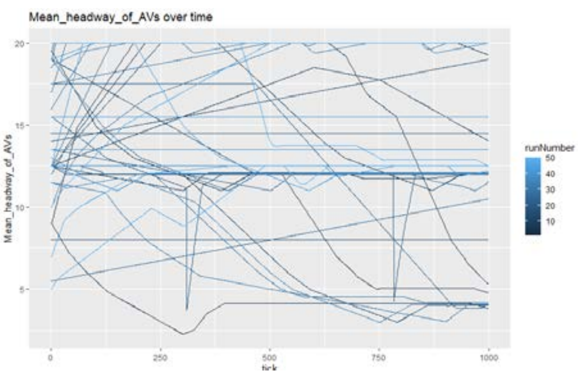

Figure C: Plot of simulation 2 model runs - mean headway experiment 1

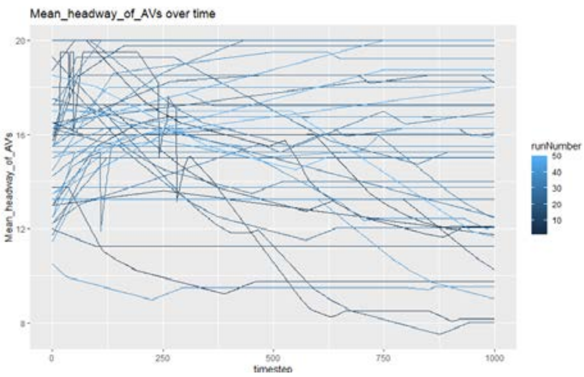

Figure D: Plot of simulation 2 model runs - mean headway experiment 2

The second conclusion is that an increased percentage of AVs in everyday traffic will cause AVs to have more headway. It can be seen in the experiment with more AVs in figure D as opposed to figure C that more AVs will also result in less diffuse headways for AVs. Also this will help reduce overtaking maneuvers on rural roads which are the main cause of head-on accidents on rural roads (Figueira & Larocca, 2020).

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 findings are that an increase in the percentage of AVs as part of the total number of vehicles will make rural roads safer. In order for traffic safety of rural roads to increase two main actions are advised. First enforcing the speed limit on rural roads and secondly encouraging the implementation of AVs.

Inhoud

Lists of Figures and Tables

Acronyms

ABM	=	Agent-based modeling
ADAS	=	Advanced driver assistance systems
AEB	=	Autonomous emergency braking
AVs	=	Autonomous vehicles
CAV	=	Connected autonomous vehicle
CoSEM	=	Complex Systems Engineering and Management
EC	=	European Commission
EU	=	European Union
EV	=	Electric vehicle
HDV	=	Human-driven vehicle
ISA	=	Intelligent speed adaptation
LKA	=	Lane keeping assist
MaaS	=	Mobility as a Service (MaaS)
MADM	=	Multi-attribute decision making
RDW	=	Dienst Wegverkeer
ROR	=	Run-off-road
SAE	=	Society of Automotive Engineers
SAV	=	Shared autonomous vehicles
SWOV	=	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid
UML	=	Unified modeling language
UI	=	User interface
V2V	=	Vehicle to vehicle
WMC	=	Working memory capacity

Preface

The initial idea for starting this master thesis about Autonomous Vehicles came in 2019 during the course for Master thesis Preparation (SEN2321). Having taken another course called Automotive Human Factors (ME41000), it intrigued me to research this topic further. I myself am very enthusiastic about vehicles in any way shape or form ranging from motorcycles to excavators. I also enjoy computers and programming, so Autonomous Vehicles I think would combine these two elements. The motivation and inspiration to pursue this topic also came from everyday life traffic behavior from motorists, bad and good. I think Autonomous Vehicles do have the potential to improve traffic flow and display good driving behavior, thereby aiding traffic safety.

I thought how could I research the implementation of Autonomous Vehicles any further? The main starting point was highway roads as this would be the most logical starting point for the implementation of Autonomous Vehicles due to their low complexity. Dr. J.A. Annema, however, proposed to research the implementation of Autonomous Vehicles for rural roads as there was not as much research on this topic yet in contrast to the implementation of Autonomous Vehicles on highway roads. The choice to research this topic with agent-based modeling apart from its methodological suitability for the subject was also because I believe in the contribution Agent-Based Modeling has to offer.

This master thesis is written in order to graduate for the Master of Science in Complex Systems Engineering and Management at Delft University of Technology. The track which I chose for this master was Transport and Logistics and I followed a minor consisting of Ethics and Automotive courses.

I would like to use this opportunity to thank my thesis committee consisting of Dr. J.A. Annema and Dr. M.E. Warnier for their support, knowhow and input on my master thesis. Dr. J.A. Annema who has helped me for a longer period of time with this master thesis. I would like to thank Dr. M.E. Warnier for his suggestions for the modeling in Netlogo and help with the visualization of model results with Rstudio programming software. I would also like to thank my family and girlfriend for finding the time to review this master thesis.

J.L. Brouwer
Delft, February 2021

Chapter 1: Introduction

This chapter consists of seven parts. In the next section the background is given for this thesis. In section 1.2 the problem will be better defined and in 1.3 research questions will be made. Following this in section 1.4 will be the methodology. In section 1.5 the current state on autonomous vehicles will be reviewed. After that the suitability for the CoSEM programme will be discussed and this chapter will be concluded by the thesis outline.

1.1 Background

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.

1.2 Problem definition

The problem definition is divided into three parts. The benefits and timeline of AVs are discussed first, secondly how AVs can use infrastructure and lastly what the knowledge gap in the literature is.

1.2.1 Benefits and timeline of AVs

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).

1.2.2 Infrastructure and autonomous vehicles

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.

1.2.3 Knowledge gap

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.

1.3 Research questions

It is clear there is a knowledge gap on how drivers of HDVs will react on the increasing penetration rate of AVs in the future on Dutch rural roads. This can result in more accidents or present itself as a barrier with the introduction of the technological innovation of AVs. Therefore the following main research question is comprised:

MQ: What are the effects of the transition phase from HDVs to AVs in the Netherlands for traffic safety on rural roads?

In order to fully answer this main research question the following eight research questions below are made, in total answering the main research question. Each of these eight research questions is a main line of a chapter in this thesis. After the effects are known, possible implications on policy will be discussed in chapter 9.

RQ 1. Which decision rules differentiate the driving behavior of HDVs and AVs? (H2)
RQ 2. How does safe driving behavior differ on rural roads from highway roads? (H3)
RQ 3. How can driving behavior on rural roads be conceptualized? (H4)
RQ 4. How can the model be formalized? (H5)
RQ 5. How can driving behavior be simulated in the model? (H6)
RQ 6. Do core concepts in the model work in a realistic manner? (H7)
RQ 7. Do patterns emerge in the model? (H8)

1.4 Methodology

To answer research questions 1 and 2, a literature study was performed. The answers to these research questions helped to create the agent-based model. To answer research questions 3 through 7, the contextual framework of the 10-step process by Van Dam et al. (2012) was used. Each of these 10 steps are presented in the table below:

Table 1: 10-step process by Van Dam et al. (2012) related to chapters and research questions

Step	Description of step	Chapter	Research question
1	Problem formulation	4	3
2	System identification and decomposition	4	3
3	Concept formalization	5	4
4	Model formalization	5	4
5	Software implementation	6	5
6	Model verification	7	6
7	Experimentation	8	6
8	Data-analysis	8	7
9	Model validation	7	6
10	Model use	8	7

The correct sequence of the 10-step process by Van Dam et al. (2012) was used but the sequence is not precisely translated to a chapter for each step. This is because the 10-step modeling process is an iterative process and that this thesis is assumed to be presented to non-ABM experts as well. The

10-step process will be explained more in depth in each related chapter for the step. The steps are to be made explicit as much as possible in the chapters 4 to 8 but are deemed as guidelines for the structure of the thesis. A choice is made to present the model validation in chapter 7 instead of after chapter 8. This is done in order to make the link between the model results and the conclusion more clear and to give more attention to the model results.

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. The 10-step process by Van Dam et al. (2012) was used because it can analyze large scale socio-technical complex systems with the help of agent-based modeling. This process was also used because it served as a blueprint.

1.5 State of the art on autonomous vehicles

Autonomous vehicles have the potential to significantly impact traffic safety. Some of these benefits were given in section 1.2.1 of this chapter. But AVs have more potential and research is continuously being done. In the next section some state-of-the-art AV related topics are discussed.

1.5.1 State of the art

An AV can choose to avoid a collision either by braking or by steering in to another lane with the help of a Multi-Attribute Decision Making (MADM) system (Gilbert et al., 2021). That system could estimate which of the two accident mitigating strategies would be best and act upon that estimation. When AVs have Vehicle-2-Vehicle (V2V) systems onboard where they can communicate with other vehicles they are called connected autonomous vehicles (CAVs). Other systems can have implications on the speed of autonomous vehicles such as connected cruise control (CCC) where the AV can increase or decrease their based on the data of the vehicle in front (Orosz, 2019).

Autonomous vehicles also have the potential to make carsharing more accessible by offering more of an on-demand style of mobility (Ambadipudi et al., 2017). These are all state of the art topics on AVs, but in the next section it will be discussed what is relevant for the case of the Netherlands.

1.5.2 Current state of autonomous vehicles in the Netherlands

With the implementation of the Experimenteerwet introduced on the 1st of July, 2019, it is allowed to experiment with AVs without having a driver physically present in the car but only with a specific permit. Also the car has to be monitored by an operator outside of the vehicle who must have a valid driving license (Rijksoverheid, 2019).

Before a permit is granted several governmental organizations will have to give their approval:
-***The Ministry of Infrastructure and Water Management***: This ministry actually grants the permit when all conditions are met and the actors below have granted their permission.
-***RDW***: The RDW, referred to as Dienst Wegverkeer is the Dutch authority for controlling and administering Dutch motorized vehicles. This actor focuses on the technical demands of the AV to ensure traffic safety as a whole is upheld (RDW, 2019).
-***Police***: This actor will determine if the risks for traffic safety have been dealt with sufficiently.
-***Road authority***: This actor can differ among several types of roads such as: the provinces, the municipalities, central government, regional water authorities and some private actors

(Rijkswaterstaat, 2020).
- ***SWOV***: The Stichting Wetenschappelijk Onderzoek Verkeersveiligheid translated to the foundation of scientific research regarding traffic safety is an independent Dutch research institute researching traffic safety.

With the permit the Dutch rules of the road from 1994 is altered to accommodate experimentation with AVs (Staatsblad 240, 2019). The desired objective of the experiment has to be a positive contribution on either an innovation on traffic safety, sustainability or traffic flow which AVs do (Staatsblad 347, 2018). The first test as a consequence of the new Experimenteerwet is the Parkshuttle concession 2018-2033. Originally driving on an industrial estate, it is now allowed to access a trajectory on a public road.

Figure 1: Parkshuttle AV to be tested on public road (Transdev, 2020)

1.5.3 Suitability for AVs in the Netherlands

KPMG ranked the Netherlands with a number 2 position in terms of its suitability to AVs in comparison with other countries (KPMG, 2020). Positives are a high amount of charging poles per person, a relatively high market share of EVs (Electric Vehicles), a clear and uniform design of roads which SWOV contributed to with the Duurzaam Veilig concept (Safe and Sustainable) and judicial room to test.

The EU also has made some legislation to further enhance traffic safety by making some Advanced Driver Assistance Systems (ADAS) mandatory for HDVs from 2022 (EC, 2019). Some relating to autonomous functions such as autonomous emergency braking systems (AEB), intelligent speed adaptation (ISA) and lane keeping assist (LKA). Thereby also reciting that the vast majority of traffic accidents are related to human errors.

1.6 Suitability for the CoSEM programme

In the Complex Systems Engineering and Management (CoSEM) Master's programme there is a great focus on an intervention in a socio-technical system due to a technological innovation of some kind. In this thesis the innovation is the introduction of Autonomous Vehicles in real-life traffic. The system of real-life traffic entails multiple aspects such as infrastructure, ethical considerations, the rules of the road, human behavior and government regulations. Some are more obvious than others. The infrastructure in this case is the road and fairly obvious but ethical considerations can be more tricky. A key ethical question could be: What is the ideal trade-off between lead distance of AVs (and therefore more capacity on the road for vehicles) and the number of traffic accidents? Such a trade-off between economical gain and safety is a hard one to make and some might even say wrong to make. This thesis designs the technological innovation into the current socio-technical system and also considers ethical issues, therefore it is a suitable thesis for the CoSEM programme.

1.7 Thesis outline

The full thesis outline together with the research question from section 1.3 is shown graphically in figure 2. After this introductory chapter the decision rules and spacing of several vehicle types will be reviewed. In the third chapter safe driving behavior is defined. The fourth chapter has a more systems based approach where the model used in this thesis is formalized. The sixth chapter displays the actual user interface of the agent-based model and defends several modeling choices. The model is verified and validated in the seventh chapter. The model results are shown in chapter 8 and concluded by the conclusion in chapter 9.

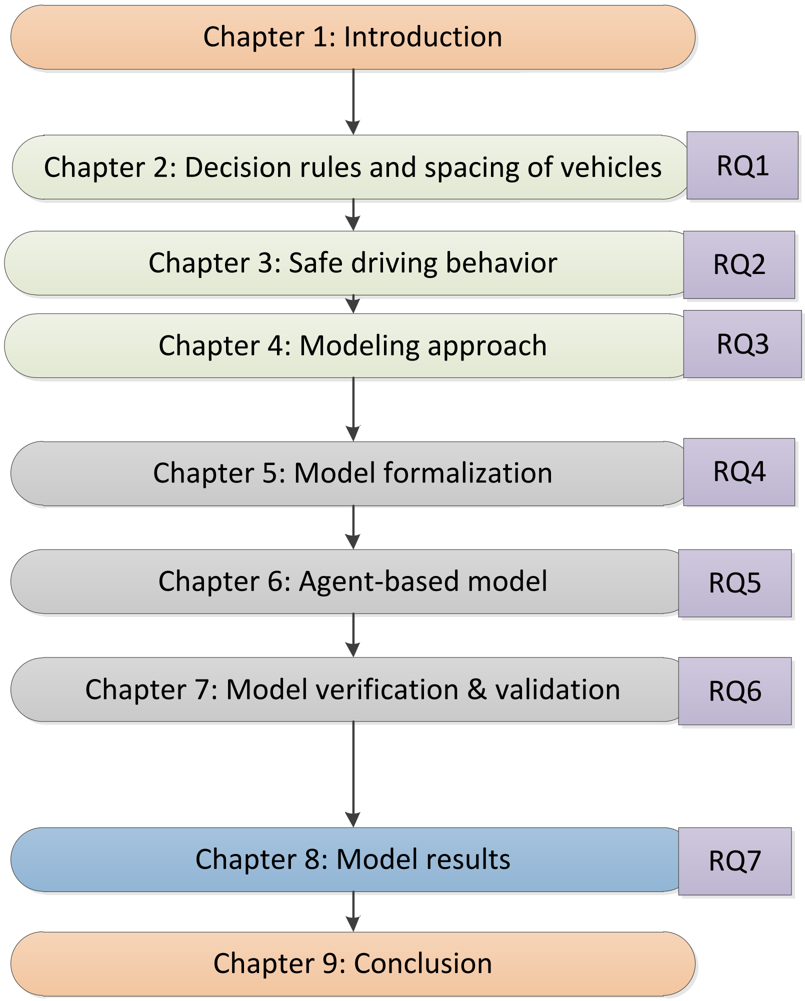

Figure 2: Thesis outline

Chapter 2: Decision rules and spacing of vehicles

In this chapter the next research question will be answered:
RQ 1. Which decision rules differentiate the driving behavior of HDVs and AVs?
In order to do so, the implementation of autonomous vehicles will be researched in 2.1 and in which manner AVs behave differently from HDVs in 2.2. In section 2.3 it is briefly discussed how this will affect the stochasticity of traffic flow. The chapter is concluded by an answer to the research question in section 2.4.

2.1 Implementation of autonomous vehicles

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.

An obstacle to the implementation of AVs will be the trust in AVs (Raats, Fors & Pink, 2020). Trust is seen as detrimental for AVs to get a noticeable market share. Trust is defined as: "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" (Lee and See, 2004). This trust can be further specified in two different user cases. One is for a driver of a Human-driven Vehicle to trust the behavior of other AVs on the road. The second is the readiness of a consumer to use an Autonomous vehicle be it either to purchase and use or to use in the case of Mobility as a Service (MaaS). In this thesis the first user case will be developed further as MaaS is not within the scope of this study. A contradiction is that humans as passengers of AVs may feel less comfortable with the driving behavior of the AV they are travelling in rather than the behavior of regular drivers (Le Vine et al., 2015). This has to do with distrusting that which is unknown, even though the AV is safer.

In order to trust automation the behavior of AVs must be predictable. Hoff and Bashir (2015) further specify trust in the three layers used by Marsh and Dibben (2003): dispositional, situational and learned trust. Dispositional trust is the trust of an agent in an autonomous vehicle or more global trust in autonomous technologies. Raats, Fors & Pink (2020) underline that trust of the user as well as public trust in AVs are essential for the implementation of AVs. The second layer situational trust is seen as trust in the environment situating the agent and is context specific. It can be broken down to factors such as self-confidence, frame of mind and discerned risks with relying on a system. The third layer is trust gained or lost from occurrences in the agents previous encounters. There is an old Dutch saying "Vertrouwen komt te voet en gaat te paard" roughly translated to "Trust is earned slowly, but lost easily". Caution must be used with the speed of the implementation of AVs for that matter.

As discussed in the previous chapter the first roads where AVs will be implemented are highway roads as they are less complex than rural and urban roads. The Society of Automotive Engineers (SAE) have defined levels of Autonomous Driving ranging from 0 to 5, level 0 being a fully manual controlled vehicle and level 5 being a fully autonomous vehicle (SAE, 2016). For highway roads an SAE level 4 car is sufficient. One of the main differences between a SAE level 4 and 5 car is that level

5 vehicles have far more intelligence to comprehend and understand the environment which is needed on rural roads.

2.2 Spacing differences between HDVs and AVs

Drivers of HDVs have spacing preferences. They may feel uncomfortable driving along with an AV close behind them but some might not have any problem with it. Driving close behind another vehicle can be characterized as tailgating, tailgating for instance is stated to be of most annoyance to Dutch drivers of human-driven vehicles in a study performed by DirectResearch (RTL, 2019). Drivers of HDVs might be annoyed by the behavior of AVs but it might also be the other way around. It can be the case that AVs need to be protected from reckless drivers of HDVs. For instance drivers of HDVs can display unsocial behavior of cutting in to a lane to make an overtake during heavy traffic conditions to gain time. If a driver of an HDV would know the AV would take the safest course of action of stopping thereby making space for the maneuver, it could chain a feedback loop of encouraging unwanted behavior from drivers of HDVs.

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.

All of the aforementioned research has looked at the introduction of AVs on a more global level but it can also be interesting to see how the introduction of AVs will lead to changes in the behavior of HDVs. This spacing preference for each individual HDV agent combined results in a system emergent type of behavior. Altogether the effects of these spacing preferences can alter traffic safety.

2.3 Autonomous vehicles and stochasticity of traffic flow

In section 2.1 the implementation of AVs was discussed, thereafter the aspects related to spacing preferences of HDVs and AVs Now the consequences of the above mentioned aspects are discussed with the implementation of AVs on traffic flow.

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.

In research done by Overtoom et al. (2020) an urban traffic study was done with Shared Autonomous Vehicles (SAVs) with the modeling software Vissim. The paper although using a different modeling approach of dynamic simulation did have some interesting modeling properties. The results of the model reported fewer traffic delays with a higher penetration rate of AVs, but the headway of the AV did have an impact on traffic delays. In the next chapter safe driving behavior is reviewed.

2.4 Conclusion

In order to answer research question 1:Which decision rules differentiate the driving behavior of HDVs and AVs? There are a number of rules which differ. The driving behavior of HDVs is more random and complex than the driving behavior of AVs. Also, in order for drivers of HDVs to accept AVs their behavior has to be predictable. AVs also require shorter lead times than AVs. HDVs will cause a more heterogeneous traffic flow than AVs and AVs have faster decision times. How this will affect safety is researched in the next chapter.

Chapter 3: Safe driving behavior

The impact of the introduction of AVs on spacing preferences was researched in the previous chapter. How it will relate to safety will be researched in this chapter. The research question for this chapter is:

RQ 2. How does safe driving behavior differ on rural roads from highway roads?

Firstly in section 3.1 driving behavior will be characterized in terms of key identification points of safe and unsafe driving behavior. In the second half overtaking is defined in terms of driving behavior and how this relates to rural roads. These two sections are necessary in order to eventually program the model in chapter 6. Finally the chapter is concluded in chapter 3.3.

3.1 Driving behavior

This section is divided into three parts. In the first part indicators for safe driving behavior are given, these indicators are discussed with the help of scientific literature. In the second section unsafe driving behavior indicators are discussed. Lastly, in the third section a specific case of unsafe driving behavior is discussed. Several papers are quoted from transport as well as psychology journals, which is plausible as driving behavior has a grave psychological component. Studies from psychological journals often made use of factor analysis thereby trying to understand the motivations of the displayed behavior.

3.1.1 Safe driving behavior

In the following section indicators for safe driving behavior will be discussed from the paper of Taubman-Ben-Ari et al. (2004). 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.

Sufficient headway: Headway is the distance to the vehicle in front. Road space can be evenly divided among vehicles causing a safer headway for both parties. It is more important for two vehicles to both have a comfortable headway rather than one vehicle having a way larger headway than the other. For example it is more than two times as dangerous for a vehicle to have a headway of 5 meters than it is to have a headway of 10 meters as the driver might have some time to react with 10 meters of headway but none with a headway of 5 meters. The response time of the driver will be highlighted next.

Perception/response time: A shorter response time gives the driver more time to react to the traffic situation and if necessary to avoid a collision (Wang, 2016). The response time is important because it is the part of the stopping distance where the vehicle is travelling at the highest speed of the braking maneuver, so a slow reaction time would significantly lengthen the stopping distance.

Speed: Speed is the most important variable in the braking distance, the braking distance is of course also effected by the deceleration rate of the vehicle which in turn is determined by the weight, grip and stopping power of the vehicle (Salehi et al., 2020). But the latter are a given of the vehicle and the speed of an HDV is ultimately determined by the driver, making it the most sensitive factor to the stopping distance of vehicles (Hsu & Jones, 2017). A higher speed also makes consequences of traffic accidents more severe. What would have been an accident at a certain speed could make a fatality at higher speed.

Calm and courteous driving: Traffic safety as a whole benefits from social behavior. The possibility of a conflict can be avoided by giving each other space. A calm and courteous driving style is characterized by patience and well-mannered behavior on the road. Patience can be observed in many instances. A motorist could have the right of way but not take it obtrusively but rather waiting in a patient manner for the other vehicle to slow down first. Also a motorist can thank the other motorist for letting them by with a simple wave at the steering wheel. These characteristics can be rather hard to quantify by vehicle statistics and must be observed by humans.

Obeying traffic regulations: Traffic regulations are designed to regulate traffic. It is therefore logical that obeying these rules will help with the regulation of traffic. Obeying traffic regulations also makes traffic more predictable. Drivers of vehicles with a high sense of responsibility showed behavior which was in line with safe driving (Vetter, 2018).

Planning ahead: Planning ahead while driving can improve safety on the road. This can be planning before the trip or during the drive. Before the trip a motorist can insure the vehicle is in a good working condition by regularly checking the technical state of the vehicle and maintaining it properly. Also they can plan on the weather and make responsible conditions because of it. When it is likely to snow it is not smart to go on the road with summer tires, only winter tires will give decent traction in snowy conditions. During the trip the driver can sensibly analyze potential traffic situations and act accordingly. For instance when a driver sees a bus at a bus stop they can choose to slow down or at least keep an eye on the situation, if indeed a passenger of the bus crosses the road without looking, if it was predicted the driver could stop earlier than if he would have ignored the bus on the side.

Paying attention to the road: Driving requires focus on the road to complete the basic driving tasks. Distractions will affect driving safety in a negative manner. Studies have been executed for drivers to warn them if they are being distracted, however it did not show a clear improvement in terms of paying attention to the road (Kidd & Buonarosa, 2017). It always starts and ends with the attitude of the drivers themselves. On a more aggregate level it was argued that although the warning system indeed warned drivers, some grabbed this opportunity to engage in more distractions because the car was safer.

3.1.2 Unsafe driving

There are many factors which can characterize unsafe driving behavior and these can be classified in certain categories. These can relate to driver status, for example a lack of sleep, but also in deliberate driver behavior. In Brewer (2010) several of these indicators are named, firstly the physical indicators are discussed and thereafter the behavioral:

Alcohol and drug usage: Alcohol usage is a factor in 25% of lethal accidents in the European Union (European Commission, 2009). For the case of the Netherlands the percentage of traffic deaths that can be blamed on alcohol is also 25% based on a study by the European Commission (EC) (European Commission, 2009).

Fatigue: Fatigue is one of the main causes of vehicle accidents. Estimated to be accountable to about 35-45% of traffic accidents. (Idogawa, 1991). However in an American Study by the American Automobile Association Foundation for Traffic Safety a much lower percentage of 16,5% was found for the United States, the latter study was far more recent (2010) than the first study which was from 1991 (Tefft, 2010).

Low attention span: A lower attention span will increase the reaction time of the driver (Louie & Mouloua, 2019). Humans only have a limited working memory capacity (WMC) so if they are taking part in another mental task it can affect their driving (Parasuraman et al., 2008). In the study by Louie & Mouloua (2019) drivers had to recite their shopping list for the supermarket and it caused a delay in drivers reaction times, negatively affecting braking distance. Obviously, a shorter braking distance reduces the possibility of a traffic accident.

Anxiety of the driver: In a study among pilots of airplanes it was found that more anxious pilots were more error prone (Beaty 1969). This also holds up for drivers of motor vehicles (Roidl et al., 2014). It can also be that drivers without sufficient skill to properly drive the vehicle create anxiety because of this reason (Roidl et al., 2014).

Work-related tension: Work-related stress can have a negative impact on driving. There is a causal correlation of stress with road accidents (Brewer, 2010: Bowen et al., 2020). With stress comes the tendency to partake in more risky types of driving behavior such as aggressive driving.

Exceeding speed limit: This is the first indicator that belongs to the deliberate negative driving behavior and not to driver status. Exceeding the speed limit has been a problem for numerous decades. Not only does a higher speed make traffic accidents more severe in terms of injuries and fatalities, it also contributes to a less homogeneous traffic flow (Brewer, 2010).

Racing, competitive behavior and risk-taking: These indicators of negative deliberate driving behavior are linked with ignorance, thrill and misplaced positive reinforcement (Brewer, 2010). First of all the drivers which partake in this kind of behavior have the tendency to believe that accidents do not happen to themselves, but that they happen to other less skilled drivers. They find a thrill in racing and competitive behavior and mistake this trill as a positive reinforcement that the trip has been driven in a more positive manner. For instance when speeding or racing a trip is completed in less time which is seen as positive and the risks which were taken will not be considered as long as the trip has been fulfilled without negative consequences. Accidents resulting in fatalities and serious injuries do not always occur because drivers are not able to drive in a safe manner, but can also occur because drivers partake in deliberate dangerous driving which fits with the risk-taking aspect (Alluhaibi et al., 2018)

Anonymity of vehicle: The anonymity of the vehicle can have a positive correlation with negative driving behavior (Ellison-Potter et al., 2001). Drivers of more anonymous vehicles partake in more dangerous driving behavior, have greater speed, more accidents and show more unsafe behavior such as negating traffic lights. It was found in the abovementioned study that the anonymity of the vehicle was a good predictor for aggressive driving behavior.

When looking at the indicators above and comparing these with the benefits of AVs in section 1.2.1 Benefits and timeline of AVs it can be seen that AVs can mitigate on the majority of these indicators. An AV shows no fatigue, no low attention span as it is constantly aware. AVs cannot be affected by alcohol and drug usage and are not anxious or can feel stress. Their programming will withhold them from exceeding the speed limit and partaking in aggressive and risk-taking behavior. The AV will also not change their behavior if it is more anonymous.

Drivers with a high level of aggression which can closely be placed with racing, competitive behavior and risk-taking in traffic have a positive causal correlation with being involved in traffic accidents (Wickens et al., 2016). In the next section a form of high level aggression by the driver of the vehicle is also discussed.

3.1.3 Road rage

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.

It is reasonable to assume that two human drivers would be necessary in this equation. An AV would never be programmed to display this kind of behavior. However there is still the option of a human driver who is not pleased with the behavior of the AV. If an HDV would engage in road rage the AV would simply take safety precautions and reduce speed or whatever it thinks is the safest option. Road rage is seen on all kinds of road types.

3.2 Overtaking

Overtaking on rural roads is a complex subject so it is divided into several paragraphs. In the next sections aspects of overtaking will be reviewed and it will be discussed how these are applicable to rural roads.

3.2.1 Motives for overtaking

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.

3.2.2 Congestion and overtaking

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.

Not specifically in the topic of overtaking but on highway lane changes Yuan et al. (2018) state that heavy traffic flow makes it increasingly complicated to complete a successful lane change. It is especially more difficult to overtake when there is maximum traffic flow, thereby having a high conflict frequency with other traffic, the authors directly relate overtaking in congestion-like conditions as less safe. In the study lane changes are studied. Overtaking could be seen as a double lane change, one from the original lane to the lane in which there is to be overtaken and then back to the original lane. So it is deemed acceptable that if heavy traffic would make lane changes less safe, it would make overtaking less safe as well.

It is also possible a driver will attempt to overtake in a heavily congested traffic situation. If that is the case the driver which will perform a lane change will need the cooperation of at least one other driver to give him space in order to achieve the desired lane switch (Zhang, 2018). But it can also be questioned if there is no room if a driver should perform a lane change at all. For overtaking this does not seem necessary and safe.

While on the topic of overtaking with an insufficient gap another study by Wilson & Best (1982) also sheds some light on this subject. It was 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. A comfortable overtake is thereby stated as overtaking without cutting in a lane or sharing a lane: both actions are deemed uncomfortable to other traffic. Cutting in a lane is defined as merging in traffic with no sufficient headway to the vehicle in front in the lane to be merged in as well as less than sufficient room to the vehicle behind in the lane to be merged in. It is then likely the vehicle behind has to brake in order to maintain a safe headway to the vehicle in front. In figure 4 the blue vehicle would cut in between the yellow and red vehicle if it were to merge at this point. Sharing the lane is the action of n vehicles next to each other in n-1 lanes, so for instance 3 vehicles next to each other on 2 lanes. The vehicle in the middle thereby drives on both lanes sharing the lanes with the other vehicles (figure 3).

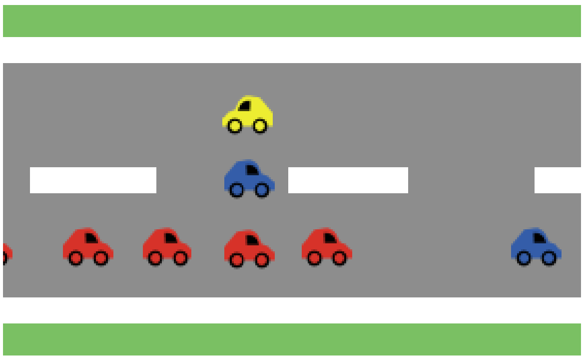

Figure 3 : Sharing a lane

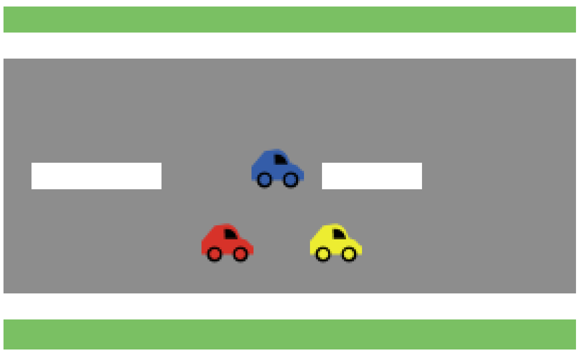

Figure 4 : Cutting in a lane

It can be concluded that if an overtake is performed while there is insufficient room the driver will need a reaction from at least one other vehicle and that the overtake will be uncomfortable for other traffic resulting in either sharing a lane or cutting in a lane for the overtake to be completed. If this is not done an accident might occur. These actions hold for lane changing on a highway, for rural roads these are mostly relevant for overtaking as rural roads in the Netherlands are mostly single lane for their respective heading.

3.2.3 Overtaking strategies

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.

The flying overtake is more likely in low traffic conditions and the accelerative overtake is more likely in heavier traffic conditions. With the accelerative overtaking maneuver the passing vehicle has a high chance of needing to decelerate after merging back into its original lane because of other traffic on that lane. Of course the driver can choose to overtake multiple vehicles at once or only attempt to overtake on vehicle at a time. In Brooks (2012) there is also some discussion on overtaking strategies on roads Pennsylvania, although these are highway roads. These two overtaking strategies focus more on the acceleration before passing the vehicle. One strategy was accelerating before passing the vehicle and passing the vehicle in front with uniform speed, the other accelerating until the vehicle has been passed and thereafter no longer accelerating. These both describe accelerative overtakes and it is thereby mentioned that the latter was used frequently and the first no so often. Logically the overtake would require the least amount of time and space if there was to be accelerated until passing the vehicle in front.

For rural roads both situations can arise but the key factor in relation to overtaking on highway roads is the oncoming traffic on the other lane. Intuitively even with high speed differences between the vehicle that wants to pass and the vehicle in front the maneuver will have taken place over a relatively large distance as speeds on Dutch rural roads vary mostly between 60-80 km/h. As such a large gap is needed even in low traffic conditions it will be likely that the accelerating overtake will be the most frequent strategy.

3.2.4 Safe overtake characteristics

For a safe overtake certain conditions will have to be met, some obvious, other less so. Some characteristics are common among scientific literature but a thorough summation is stated in Hassan et al. (2014). An overtake can be defined in three sections: the factors which influence the decision to execute the overtake, the factors which actually result in the success of the overtake and some external factors not directly related to the driver.

The factors which influence the decision of the driver to execute the overtake are their personal belief in that the overtake will be executed successively, the risk the driver is willing to take in terms of a percentage that the maneuver could end up badly and his frustration level. With a higher frustration level, more risks will be taken. This can even add up: when a driver misses an overtaking opportunity it can frustrate them even more and make them more likely to perform an unsafe overtake (Steierwald et al., 1983).

The factors which actually influence the success of the overtake in physical terms are:

- The distance ahead to the vehicle on the other lane
- The distance to the vehicle in front
- The speed of the vehicle in front
- The free space in front of the leading vehicle
- The length of the vehicle ahead

A safe overtake consists of an overtake with sufficient overtaking margin. It is safe when a dangerous situation is not created, no vehicle is hampered and sufficient space is left on the criteria mentioned above. It can happen that an overtake is executed but halfway through the driver realizes they can't complete the move in a safe manner. Whether it ends up without an accident depends on the actions of the other vehicles involved, the decision time of the driver of the overtaking vehicle and the width of the road (Hassan et al., 2014: Richter et al., 2017).

3.2.5 Overtaking on rural roads

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. Head-on collisions have caused the most significant number of deaths (Figueira & Larocca, 2020). This is not surprising, with an accident on a highway one could for instance drive 120 km/h and crash into slow or not moving traffic giving a net residual speed of 120 km/h. On a rural road if there were to be a frontal collision the driver who overtakes has raised their speed above the limit of say 80 km/h and crashes into the vehicle on the opposite lane netting a residual speed of at least 160 km/h. Thereby not even taking into account the mass of the vehicles, of course consequences will be more grave with trucks. The type of vehicles which generally drive on rural roads are trucks and cars (Richter et al., 2017).

Road markings and signs can help with reducing accidents (Richter et al., 2017). For instance a crossed line not to overtake before a turn. The traffic distance necessary for an overtake becomes larger with a higher speed of the vehicle. When both speed limits and overtaking restrictions are legislated, are rural roads at their safest. The width of the road can also have some impact. A small effect is seen in Richter et al. (2017) but not very clear. Intuitively it would make sense for it to be safer as backing out of an overtake would be easier.

3.3 Conclusion

In order to answer research question 2: How does safe driving behavior differ on rural roads from highway roads? 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.

Chapter 4: Modeling approach & system identification

A literature review was done in the previous two chapters to research how AVs will likely impact traffic safety. The chosen modeling approach of agent-based modeling is explained in the first half of this chapter in section 4.1. As described in the methodology in section 1.4 this chapter will begin with the 10-step modeling process by Van Dam et al. (2012) in the second half of this chapter in section 4.2, namely step 1 and step 2. The following research question will be answered in this chapter:
RQ 3. How can driving behavior on rural roads be conceptualized?

4.1 Modeling approach

The modeling approach is defended by first explaining why agent-based modeling is beneficial for the problem situation and secondly why it is suitable for the system.

4.1.1 Why Agent-based modeling?

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.

The behavior displayed in an ABM can originate from two levels: an aggregate emergent level and a lower agent level. The interaction of conventional drivers and the programmed behavior of the autonomous vehicles will cause emergent behavior. As emergent behavior might seem complicated from a systems point of view, it stems from simple individual agent rules. These rules are used every time step and are more realistic than mathematical equations and can be understood without knowledge of complex mathematical formulas (Wilensky, 2015).

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. A final disadvantage is that the inner workings of the model will need to be explained, this will be done in chapter 5, in the model formalization.

4.1.2 Suitability

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.

As ABM is a computational method, it can simulate a model taking certain parameters into account such as lead time, size of the vehicle, speed and several other factors. An ideal-type model will be used that simplifies some of the complexity such as the aggressiveness of drivers of HDVs, acceleration & deceleration and performing an overtaking maneuver. This will be done because it would have little effect on the operation of the model without reducing insight taken from the model. The 10-step process of building agent-based models is used as described in the book 'Agent-Based Social Systems' by Van Dam et al. (2012). ABM can be performed with the modeling software Netlogo which is created by Uri Wilensky.

4.2 System identification

From this point on in this master thesis the 10-step process by Van Dam et al. (2012) is closely followed.

4.2.1 Step 1: Problem formulation and actor identification

Components of this first step have already been reviewed in chapter 1 to 3, so this will be quickly reviewed without being too repetitive. 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. The better the technology of AVs the safer they will be.

The problem owner in this case is the Dutch Ministry of Infrastructure and Water Management (Ministerie van Infrastructuur en Waterstaat). This Ministry is responsible for a safe, accessible and liveable Netherlands regarding transport connections (Rijksoverheid, 2020). The main actors involved with the initial experiments of AVs on Dutch roads are the police, SWOV and the road authority that can differ per road. Other actors that have relevance are:
-***AV manufacturers:*** The manufacturers develop and produce AVs although this is currently more leaning towards development than producing.
-***Drivers:*** Motorists choose any number of vehicles.
-***TNO*** is another actor which is relevant. TNO (the Netherlands Organisation) for applied scientific research helps with the development of Autonomous Vehicles and sets standards for the Dutch Government (Ministry of Infrastructure and Water Management in this case) in terms of ethics, laws and standards of society (TNO, 2020).

4.2.2 Step 2: System identification and decomposition

When choosing the aggregation level of the system it is important to note that the introduction of AVs will impact other traffic directly. It is therefore logical, especially when taking the modeling approach in mind, to look at the system at an agent level of traffic and not on a more aggregate level. Even though the problem owner does not directly take part in traffic, it is responsible for it. When looking at traffic at rural roads the most common types of vehicles are conventional HDVs such as cars and trucks. Cars will from this point on be referred to as an HDV and trucks will just be referred to as trucks. Of course a third vehicle type to be introduced within the model is the AV.

All vehicle types have a preference for a desired speed or a preference for a (spacious) position on the lane. Vehicles interact with each other by noting the distance to each other and noticing their speed. Actions can be taken upon that information by accelerating or decelerating in a longitudinal manner. When overtaking vehicles must move to another lane in order to overtake on a rural road. Vehicles must also note crossing traffic coming from the sides on rural roads which is different from highways. Vehicles are bound by law to adhere to the maximum speed but are physically capable of exceeding the maximum speed limit.

All agents are motorists and they have a certain actual speed, a desired speed and a maximum speed limit which is set for the road. If there is no conflicting traffic in the way the vehicle will try to speed up to its desired speed. It will only slow down if other slower traffic is in front of them. Only a driver of an HDV will try to overtake a vehicle in front if there is space and will become frustrated if they can't. AVs are programmed to not overtake, such a dangerous maneuver in the introduction phase can harm the reputation of AVs if it will lead to an accident. Trucks don't lend themselves very well for overtaking due to their slow acceleration characteristics and vehicle size so trucks will not overtake also. Each vehicle type has a specific size. If a driver comes into contact with another vehicle it will register as an accident. Each agent has a right of way or not depending on the lane they are in.

The environment in which the agents interact has specific properties. The environment entails the roads on which the vehicles are able to drive on or where they are not able to drive on. The vehicles can also drive over the white painted lines on the asphalt. There can be intersections with crossing traffic on the rural road. The road authority dictates the speed limit which is set on the road and if there is an overtaking prohibition or not. The weather is of influence to all motor vehicles. There can be multiple lanes on a rural road, although this is not as common on a rural road as it is on a highway or there can be two lanes on which the second lane has an opposite heading. The amount of vehicles is a given for each vehicle, a vehicle can't decide how much traffic is on a specific road. A graphical summary of the last three sections is given below.

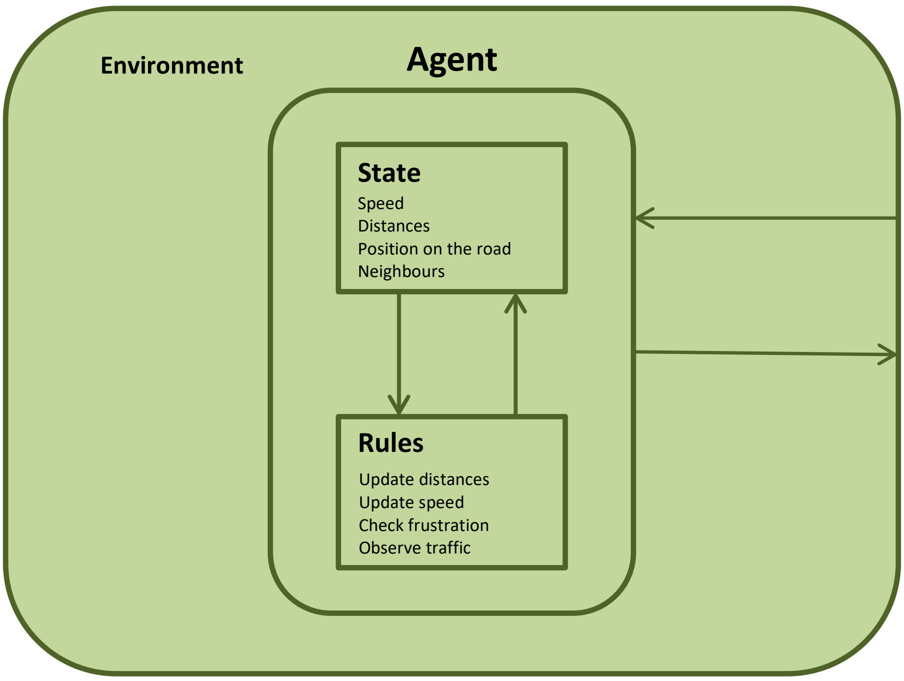

Figure 5: System Identification

Chapter 5: Model formalization

This chapter will consist of two parts of the 10-step process by Van Dam et al. (2012) namely step 3 and 4. The first section will consist of the concept formalization and the second section will consist of the model formalization. The research question to be answered in this chapter is:
RQ 4. How can the model be formalized?
The answer to this fourth research question will be given in the conclusion.

5.1 Step 3: Concept formalization

As described in section 4.2.2 there are two main types of vehicles on Dutch rural roads: cars and trucks. With the introduction of the autonomous vehicle there would be three main types of vehicles on Dutch rural roads. These are displayed in the ontology in figure 6 below.

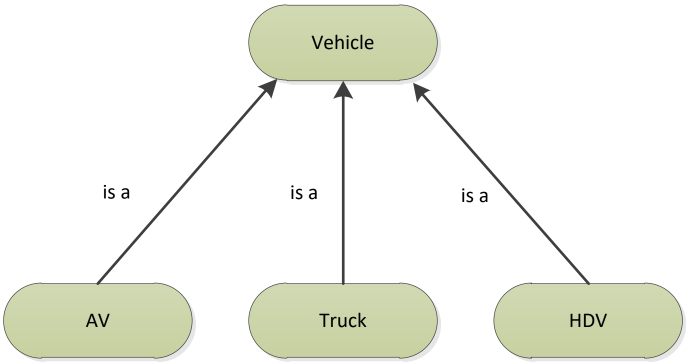

Figure 6: Ontology

From this point on each car which is not autonomous will be considered an HDV, so there will be three vehicle types: Human-driven vehicles (cars), trucks and autonomous vehicles.

In order to formalize the concepts discussed in the previous chapter, the system concepts will have to be formalized into software data structures. Each variable in the text of section 4.2.2 has been formalized and put in a unified modified language-diagram (UML-diagram) in figure 7. In this diagram the relations between the vehicle types become more clear. It can be seen in the UML-diagram that a vehicle is a class, it is also a generalization of an HDV. An HDV differs from trucks and AVs in the sense that it has some extra variables which relate to overtaking which an HDV can and trucks and AVs can't. A vehicle can drive on a road which has certain properties. Variables of these classes will be formalized to give a detailed description of each variable. The formalization of each of these variables will be described in the tables 1-3 below, each table belonging to a class in the UML-diagram.

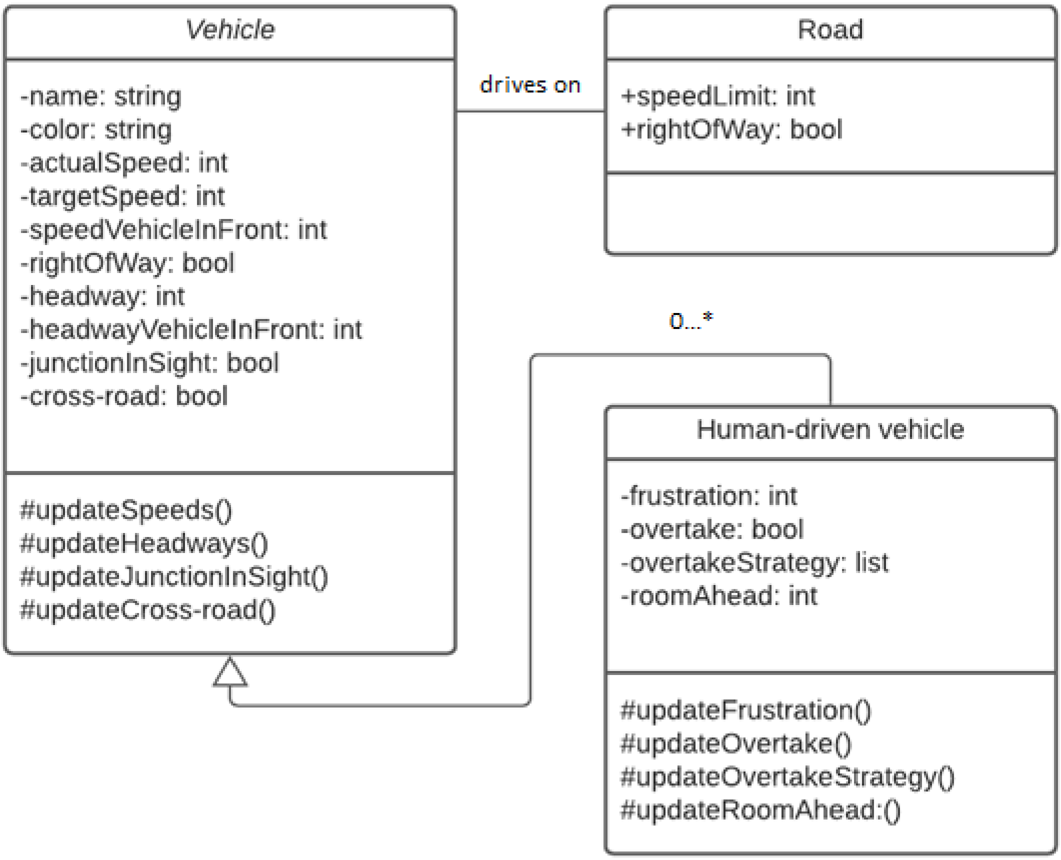

Figure 7: UML Class Diagram

Table 2: Formalization of vehicle class

Variable	Description	Class	Unit
Name	The name given to each vehicle for instance: AV01	String	-
Color	Each vehicle type is given a color. A truck is blue, an HDV is red and an AV is yellow.	String	-
Actual speed	The actual speed a vehicle is travelling at	Integer >= 0	Km/h
Target speed	This is the speed a vehicle would like to reach	Integer >= 0	Km/h
Speed of the vehicle in front	The actual speed of the vehicle in front	Integer >= 0	Km/h
Right of way	A true or false if a vehicle has right of way or not.	Boolean	True/False
Headway	The distance to the vehicle in front	Integer >= 0	Meter
Headway of vehicle in front	The distance between the vehicle in front and the vehicle in front of that one, used to determine if there is space in front of the vehicle in front	Integer >= 0	Meter
Junction in sight	If there is an intersection nearby or not	Boolean	True/False
Cross-road	A Boolean to determine if a vehicle is crossing the road from a side road which does not have right of way	Boolean	True/False

Table 3: Formalization of human-driven vehicle class

Variable	Description	Class	Unit
Frustration	An HDV can be frustrated if its target speed is higher than the speed it is actually driving	Integer >= 0	-
Overtake	A true or false so an HDV knows if it is executing an overtaking maneuver.	Boolean	True/False
Overtake strategy	There are two overtaking strategies as discussed in section 3.2.3. There is the flying overtake and the accelerative overtake.	List	-
Room ahead	The room ahead is equal to the headway of vehicle in front, it is created to determine if there is room to merge back into the lane after overtaking.	Integer >= 0	Meter

Table 4: Formalization of road class

Variable	Description	Class	Unit
Speed limit	This is the speed limit which holds for the road	Integer >= 0	Km/h
Right of way	If the road is a road with right of way or not	Boolean	True/false

There is also a method section in the lower part of each class in the UML diagram in figure 7. There it is stated which variables are updated with each modeling step. As can be seen in the vehicle class the actual speed of a vehicle is updated for modeling step. The model color is not which is logical since a vehicle cannot switch between a vehicle instance. In the next section the model is formalized further by specifying when a certain agent takes a certain action, agent behavior will be specified next.

5.2 Step 4: Model formalization

In the model formalization the concept from the third step is narrated per time step in section 5.2.1. After that it is translated into bullet points in section 5.2.2

5.2.1 Model Narrative Example, Actions per Time Tick

First of all the road on which the vehicles drive on is created. The road can have none or multiple side roads and has a speed limit. A vehicle is created and put on the road accounting some minimum headway between itself and the vehicle in front of it and to the rear of it. The agent realizes if it has right of way on the road it's driving on and based on that information drives forward or not. On rural roads there is crossing traffic, if driving near a junction one must have right of way or otherwise stop, one can only cross the road from a side road if the junction is free. The vehicle can also decelerate if the headway to its predecessor is too short and the vehicle in front is driving slower than him.

Vehicles will accelerate if they can do so to the speed limit. Vehicles must maintain headway to not drive into the vehicle in front, only an HDV will try to overtake if there is an opportunity to do so. An HDV can have two overtaking strategies: an accelerative overtake or a flying overtake. A driver of an HDV will get frustrated if its actual speed is lower than its desired speed. In order for an HDV to overtake it must take into account its speed, the speed of the vehicle in front, the size of the vehicle in front, if the vehicle is nearing a junction or not, the distance to the vehicle in front and if there is room to merge after passing the vehicle in front. AVs are not allowed to overtake due to their programming software. Trucks are not allowed to overtake on rural roads.

5.2.2 Narrative in bullet points format

The software model can be largely divided into three parts:

1. The road and the vehicles have to be created.
2. Vehicles have to be created with their initialization properties.
3. Vehicles move and check their surroundings and properties during each model tick in order to know how they should move.

Parts 1 and 2 are the initial properties of the model. Only part 3 has a discrete continuous nature in order for the vehicles to move. In order to translate the model narrative into programming software it has been formalized for each of the three parts in the summaries below.

The road and vehicles have to be created (part 1 of the programming software)

- The main rural road has to be constructed
- Intersections have to be constructed if applicable
- The environment has to be created
- Create vehicles

A vehicle initializes its properties and distances to other vehicles nearby, it: (part 2 of the programming software)

- Checks vehicles speed in front
- Checks distance to vehicle in front
- Checks if there is a junction coming
- Checks if there is room in front of vehicle in front
- Checks if there is room on the opposing lane to overtake
- Checks if it can cross a road when it has no right of way
- Recognizes right of way depending on the road the vehicle is driving on

A vehicle perceives its own entities, it: (also part 2 of the programming software)

- Checks its own frustration = if desired speed-actual speed is positive frustration builds
- Checks the maximum speed limit and its own speed

A vehicle drives and repeats part 2 during every tick and it: (part 3 of the programming software)

- Accelerates if speed is lower than its desired speed, the speed limit, if the distance to vehicle in front is big enough or it is overtaking
- Decelerates if speed is higher than vehicle in front, there is not enough headway and is not overtaking
- Crosses a junction if it can cross a junction on a road which does not have a right of way = Vehicle must check if there is a sufficient gap on both lanes in order to cross the lanes
- (HDV only) Overtakes if frustration level is above threshold AND vehicle speed in front is lower than its own speed AND (the size of the vehicle in front + the room in front of that vehicle is big enough to merge back into traffic) AND there is no junction in front AND there is space on opposing lane
- Moves forward

5.3 Flowcharts

In order to translate the bullet points from the previous section to programming language these bullet points are translated to pseudo-code in Appendix A, because this is quite hard to read this pseudo-code has been translated to flowcharts. Flowcharts can visualize decision rules of the model. First a smaller flowchart is constructed to show how part 1 of the previous section is formalized, secondly two bigger flowcharts will explain the inner workings of part 2 and 3 of the model.

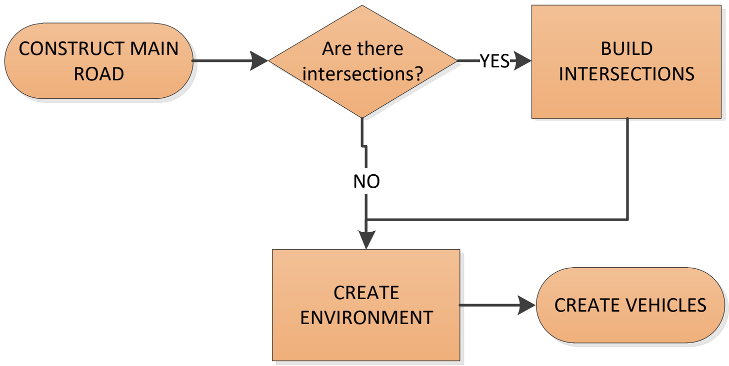

Figure 8: Flowchart part 1

In the figure above the flowchart of the starting conditions of the model is visualized. These are the rules the model follows with the initialization of the model. The flowchart above and the flowchart below both use colors to identify themselves with the process. Orange is step 1 and creates the starting conditions. Green in figure 9 on the next page represents the properties and distances to other vehicles and purple represents the entities the vehicle itself checks. Technically the maximum speed limit is not set by the agent itself but this will be programmed as a property of an agent. The pink flow-diagrams represent the decisions and processes which are checked during every tick within the model.

5.4 Conclusion

The research question to be answered in this conclusion is RQ 4: How can the model be formalized? The model has been formalized by firstly formalizing the concept with the help of software data structures, a UML-diagram and by specifying the variables. Secondly thereafter the model has been formalized by narrating it and translating it into bullet point sentences. These three parts of bullet points should not be confused with modeling steps: they are in essence all step 4. Lastly flowcharts have been constructed to help with the next step in the modeling process, step 5: software implementation. All of these rules and decision structures have to be translated into programming software in the next chapter.

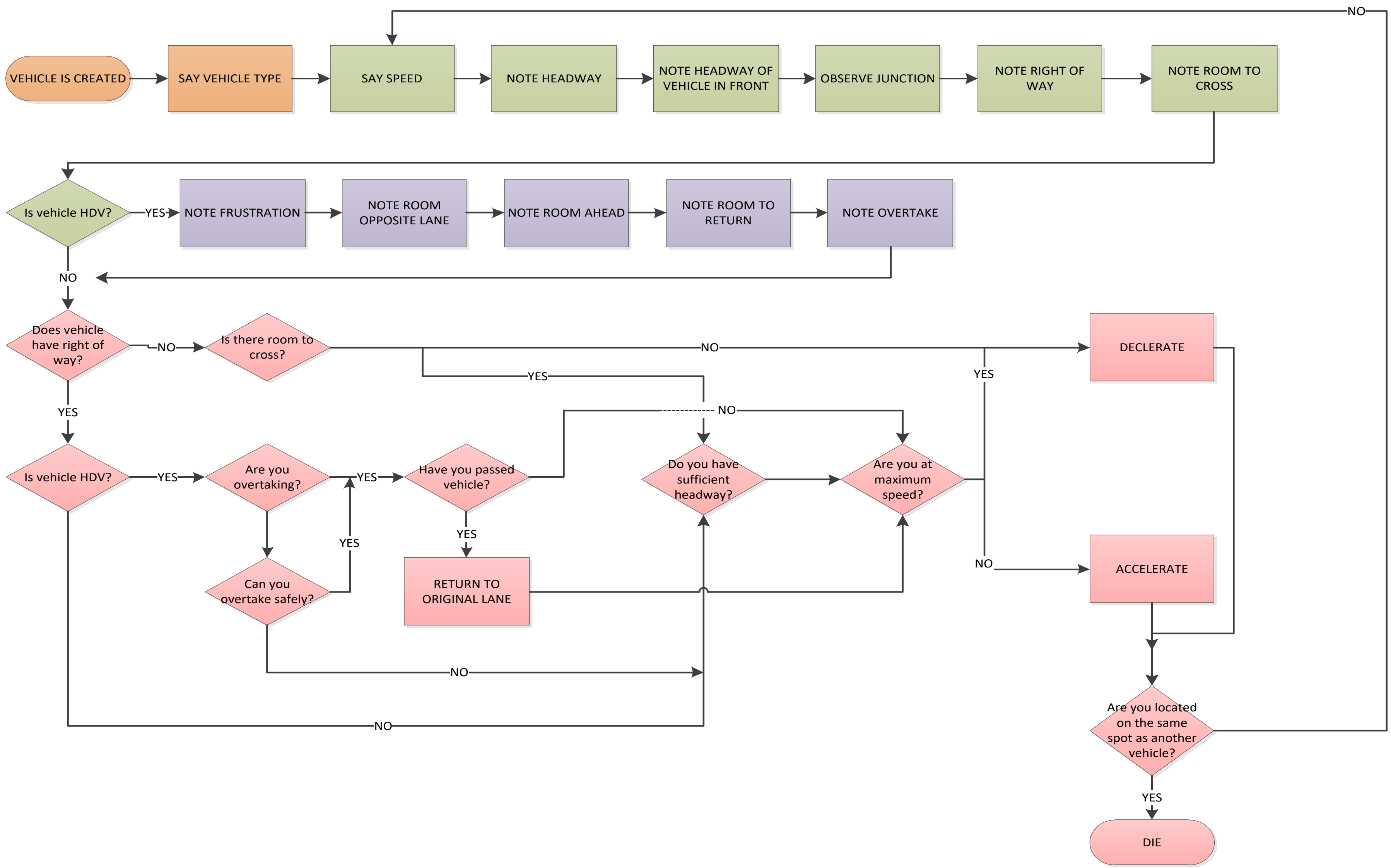

Figure 9: Flowchart part 2 and 3

Chapter 6: Agent-based model

The agent based model has been programmed for step 5 of the 10-step process by Van Dam et al. (2012), namely the software implementation. The result of the fifth step is shown in the following sections. The interface will be explained in section 6.1 and how to use the model will be explained in section 6.2. Furthermore some simplifications are summarized in section 6.3. The research question is as follows:

RQ 5. How can driving behavior be simulated in the model?

6.1 Model interface

The agent-based model is programmed in Netlogo written by Uri Wilensky. The model is called HDVs, trucks and AVs.nlogo. The model code is present in appendix B. A screenshot of the model is made in figure 11 on the next page, it is not a full screenshot of the user interface (UI). All the buttons, sliders, switches, monitors and plots are depicted but the actual world in the model file is two times as wide, this was done so all the text was readable in the figure otherwise it would have been cropped to an unreadable size. The world is 61 patches tall and 101 patches wide.

In the top left corner of figure 11 are the setup and drive button to initialize and run the model. Below that are three sliders to create the number of vehicles, each type of vehicle must be chosen between 1 and 5. The simulated world is small so if there were to be more vehicles it would make it impossible to simulate overtaking or the number of vehicles would simply not fit in the model and it would crash. Monitors for each vehicle type are present to display the number of vehicles per type and for verification purposes there is also a total number of vehicles. Below that are two switches which could add 1 or 2 intersections separately to the model.

Further below that are two impactful input selectors (sliders) for the model. One sets the maximum speed limit between 60-80 km/h. The other sets the heterogeneity of the speed as the speed of the HDVs can fluctuate based on driver preference. The speed is graphically depicted below that.

The second column consists of more input sliders, switches, monitors and a plot. Vision relates to how far all vehicles can see when looking for intersections. Side-vision and angle of vision relate to how far and at which angle vehicles from the side road can perceive vehicles with the right of way on the main road as depicted below in figure 10.

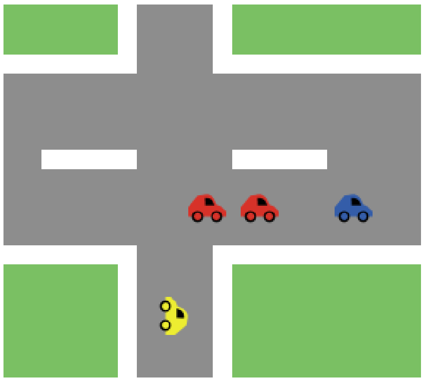

Figure 10: Vehicle looking to cross

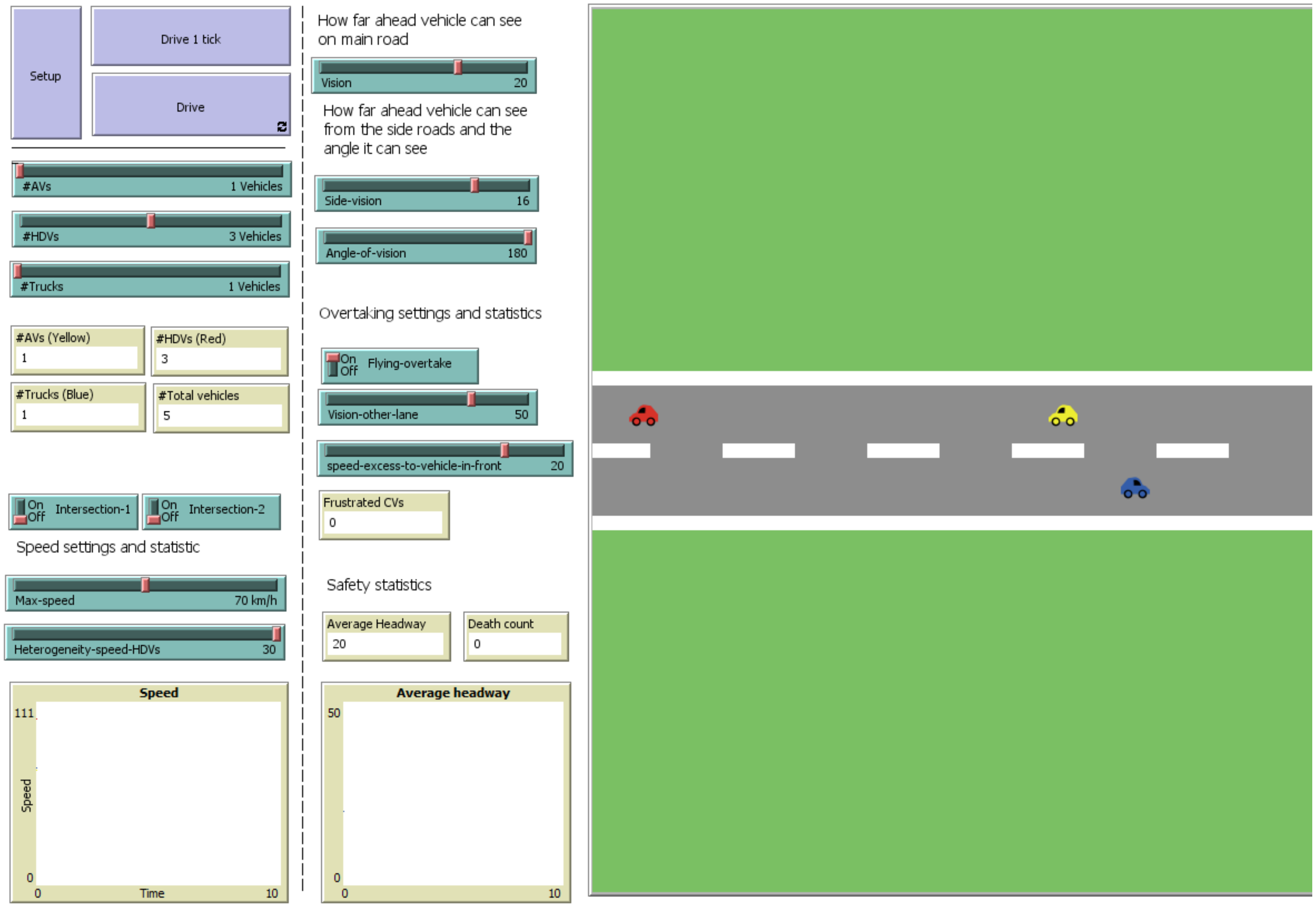

Figure 11: User Interface agent-based model

Directly below the vision sliders are four variables related to overtaking. The first is a switch which switches between overtaking strategies. With *flying overtake* switched on, the vehicle can overtake without having to build up frustration, with the off-setting for *flying overtake* this is mandatory. The vision other lane relates to how far an HDV can see on the other lane to assess if overtaking conditions are good enough. The speed excess to vehicle in front relates to the minimum speed discrepancy needed for HDVs to perform an overtake. A smaller excess would be more dangerous as the distance would be longer. In the final bottom left section are some safety statistics for measuring traffic safety. The advised model speed is to be set at 25% of the total speed halfway between slow and normal speed in order to visually observe the behavior of the vehicles.

6.2 Data, model choices and selected variables

In order to program the model data was required. The selected speeds of the rural roads is set via an input slider between 60-80 km/h because these speeds are common on rural roads (SWOV, 2004). These speeds can vary more even between 30-100km/h, but the 30 km/h speed limit would be for dangerous sections and the 100km/h would mostly be for highways so it was chosen to omit these speeds.

In the model it is chosen to have AVs adhere the speed limit because AVs have a lot of technology on board and have GPS where they can accurately measure their speed. As truck drivers frequently have tight delivery schedules, it is likely that these tight schedules would make to closely adhere to the speed limit or exceed it with a tight margin. These tight schedules can even lead to increased risk-taking behavior and non-compliance of speed regulations (Chen et al., 2021). It was chosen that they drive a little faster than the speed limit but within the speed measurement correction of 3 km/h to prevent fines (Consumentenbond, 2020). The speed of the agents is realized in the setup part of the model code, this next section directly relates to the programming of those speeds.

ask AVs [set speed max-speed set target-speed speed]

ask trucks [set speed max-speed + random 3 set target-speed speed]

*ask HDVs [set speed (max-speed - (random heterogeneity-speed-HDVs) + (2 * (random heterogeneity-speed-HDVs))) set target-speed speed]*

It was decided to show heterogeneity in the speed for HDVs because conventional drivers differ in their speeds. One driver might have different preferences than other drivers. In chapter 3 of this thesis several indicators were depicted for safe or unsafe driving behavior. It was concluded AVs have the potential to affect the stochasticity of the traffic flow making it more homogeneous and safer. To make the heterogeneity of the traffic flow for HDVs variable could lead to insight on the impact of AVs on traffic flow. This heterogeneity is modeled in a uniform distribution. So a heterogeneity of 10 would make HDV speeds on a 80 km/h rural road differ between 70-90 km/h.

The safety statistics chosen in this model are headway of vehicles, death count and speed. Several safety statistics have been reviewed in chapter 3 but not all are feasible to model. One such example is work-related tension, yes it does affect driving behavior but it lies outside of the scope of this study. Some other simplifications have been made, these are discussed in the next section.

6.3 Simplifications of ABM model

For this model some simplifications were made which were deemed not relevant to the model. One of these simplifications is that emissions do not play a role. In chapter 2.3 it was noted that a more heterogeneous flow does impact emissions but it does not affect traffic flow so it is omitted. The second simplification is that HDVs and AVs have the same vehicle size. As the world is relatively small compared to an actual rural road it was disadvantageous to implement a bigger vehicle size for trucks. It was deemed it would not affect the traffic flow mechanisms but the higher vehicle speed is implemented though as this would impact traffic safety directly. More complexity does make a more realistic model but a too detailed model takes more resources and distracts from the core model mechanisms.

6.4 Conclusion

This chapter has shown how the model can be used to simulate driving behavior, which variations can be made in order to alter driving behavior and to show some important modeling choices. These model choices also were simplifications in some respect. The next chapter shows how the model is tested before the model is used for experiments in chapter 8.

Chapter 7: Model verification, validation and sensitivity analysis

The model verification, validation and sensitivity analysis are reviewed in the seventh chapter of this thesis. In the first part of this chapter are a few examples of why the model is coded right. In the second part are examples of techniques to display that the model follows real world behavior patterns and that findings can translate to the real world. These relate to step 6 and 9 of the used modeling approach, step 6 relating to the verification and step 9 to the validation. A sensitivity analysis is also performed to see where the model is sensitive to. The next research question is answered in this chapter:

RQ 6. Do core concepts in the model work in a realistic manner?

7.1 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 properties of a single agent were followed as displayed for the case of an HDV in figure 12 below. The model was simulated several times at low speed with the help of tracking the agent to solve unwanted behavior.

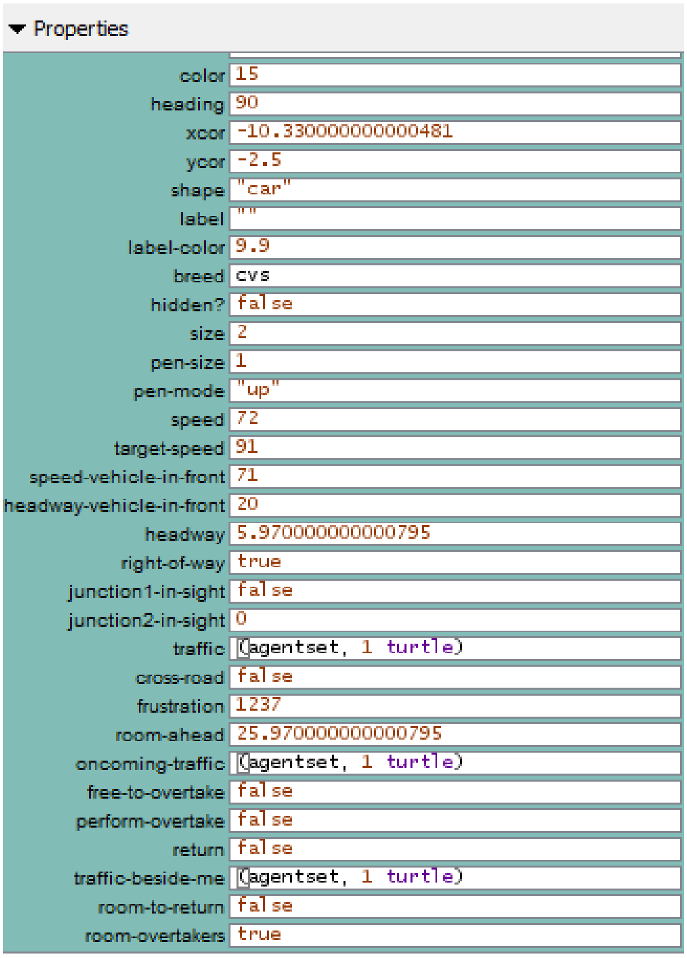

Figure 12: Properties of a single HDV agent

Another technique used is 'breaking the agent' by Van Dam et al. (2020). In this technique extreme values are given to input variables in order to break the agent. With such extreme values such as limited vision and low thresholds for overtaking there were a lot of deaths of agents in the model which is logical. A flaw in the model was corrected where agents drove backwards, the agents are only expected to drive forwards. The 'multi-agent testing' technique used from the same source as above did not have an unwanted effect on agent behavior.

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). For example if a vehicle with a heading of 90 and an x-coordinate of 40 would note the headway of a vehicle 15 patches in front, that vehicles x-coordinate would be -45 as the world wraps, thereby making the headway -45 – 40=-85 which is not right. Adding 101 would give its correct headway of 16 patches ahead (15 patches + 2*0,5 patch the vehicles are standing on). A correction in the model code for this phenomenon is displayed below:

> *if heading = 90 [if headway < 0 [set headway (headway + 101)] if headway > 20 [set headway 20]]*
>
> *if heading = 270 [if headway < 0 [set headway (headway * -1)] if headway > 20 [set headway ((headway * -1) + 101)] if headway > 20 [set headway 20]*

A modeling choice is that the maximum headway is set to 20 patches as a maximum. A larger headway would affect the mean headway of vehicles statistic too much and add no benefit for safety purposes. Next, the validation is discussed.

7.2 Validation

It can be hard to validate an agent-based model as there have been numerous simplifications and the real-world model with the implementation of autonomous vehicles is not present. This argument was also given in section 4.1.1 and stated by Kagho et al. (2020). 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, the papers are discussed in the following examples. 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. On the left in figure 13 is the headway of AVs, aggregated in a cumulative distribution of the paper by Ivanco (2017). On the right is the mean headway of autonomous vehicles produced by a model run with 4 AVs, 1 truck and 2 AVs. The curves are similar in curvature although the model of figure 14 produces a less smoother line, this is assumed to be the case because the model of figure 13 has more autonomous vehicles (14 AVs) than the model in figure 14 (4 AVs) and this will likely smoothen with more vehicles.

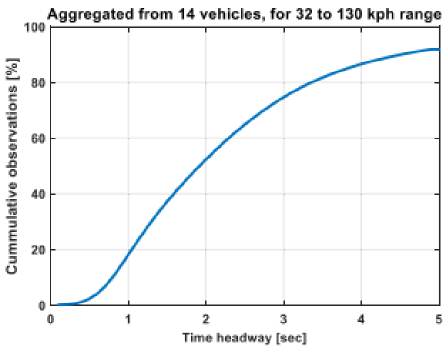

Figure 13: Headway of vehicles (Ivanco, 2017)

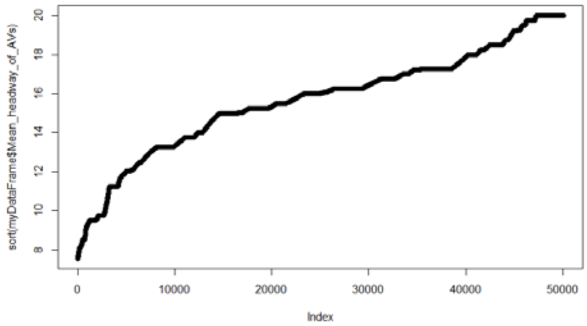

Figure 14: Headway of AVs from a model run

In the model the headway is maintained through a distance-based approach. In a scientific paper by Micó et al. (2018) driving techniques are compared between a distance-oriented approach and a inertia-oriented approach. Figure 15 shows two lines, the bottom darker line is for the distance-based approach and the lighter line is for the inertia-based approach. The distance-based approach closely resembles the behavior of a Netlogo model run in figure 16 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.

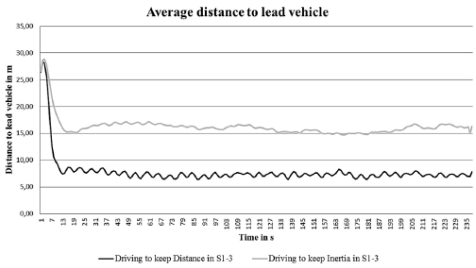

Figure 15: Mean headway of HDVs (Micó et al., 2018)

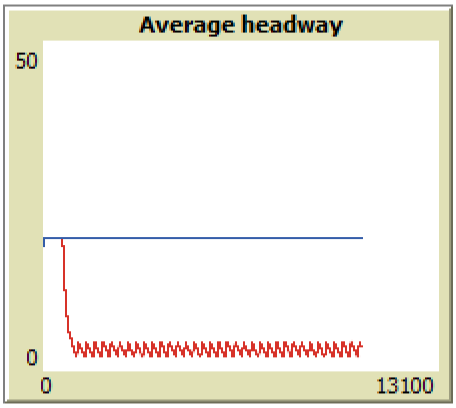

Figure 16: Headway of HDVs from model (red)

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.

7.3 Sensitivity analysis

In order to measure how the uncertainties of the input variables will affect the model, a sensitivity analysis is performed. The output variables to be measured are average headway of all vehicles, the number of frustrated HDVs and the death count. Speed is also a factor which is mentioned in the literature study of chapter 3 as a contributing factor for unsafe driving behavior, so speed will also be varied. Several indicators have fairly predictive or similar behavior and others are relatively uncertain. Input variables are altered and the results are discussed.

The model has several input variables which are tested:

- *The mix of AVs, HDVs and Trucks*: Each of these vehicle types can be set from 1 to 5, so a total population of 3-15 vehicles can be created. A larger population will cause the average headway of vehicles and the number of overtakes to drop and thereby death counts to reduce as there will be little space on the opposite lane for an overtake. The average headway and death count are sensitive to the total population.
- *Turning intersections on and off*: When these switches are turned on, less overtakes by HDVs will be performed because an HDV will not perform an overtake if there is an intersection in sight. This will cause HDVs to stay behind the vehicle that is in front of them and will keep them frustrated and shorten their headway. But this will cause fewer overtakes so the death count will be lower.
- *Max-speed*: A higher speed will cause an overtake maneuver to cover more distance as both vehicles travel more distance. This will also cause more deaths. The number of attempted overtakes is mildly sensitive to the max-speed.
- *Heterogeneity-speed-HDVs*: The higher this setting is the more differences in speed there will be so there will be more overtakes. The death count is especially sensitive to this variable.
- *Vision*: This relates to observing intersections. Because HDVs on the main road are programmed to not overtake with an intersection in sight, a higher vision setting will result in less overtakes. But this variable is not particularly sensitive as vehicles from side roads also perceive traffic on their own.
- *Side-vision & angle-of-vision*: Both input variables are safest when they are high. When they are low, vehicles from the side roads are basically crossing without looking which is dangerous. The model is sensitive to low values of these variables.
- *Flying-overtake*: This switch turned on will cause faster and therefore safer overtakes as HDVs will have a higher initial speed. Faster overtakes will result in a lower number of deaths. But it will not affect headway or the number of frustrated HDVs. The model is mildly sensitive to this variable.
- *Vision-other-lane*: This is one of the criteria in order for HDVs to attempt an overtake. Lowering this will cause HDVs to overtake in smaller gaps, which is dangerous and will lead to more deaths. The model is sensitive to low values of this variable.
- *Speed-excess-to-vehicle-in-front*: This is a variable which has a large impact on the number of overtakes and deaths, so the model is sensitive to this variable. Putting this input variable to the lowest setting of 5 will result in HDVs attempting to perform an overtake while their speed is only marginally faster than the vehicle in front, effectively causing a large distance needed in order to perform the overtake safely. Once an HDV attempts an overtake it can’t back out of the model. So if it overtakes and a large distance is needed it can encounter traffic on the other lane and cause an accident.

A large number of these input variables have fairly predictable outcomes, some with a large impact and some input variables have similar outcomes when altering their values. Lowering vision-other-lane and speed-excess-to-vehicle-in-front for example will both cause more and more dangerous overtakes. The heterogeneity of speed of HDVs is predicted to have the biggest impact.

Chapter 8: Model results and analysis

The model results are depicted in this chapter. The input parameters for the model are explained first. The second section of the chapter contains two model tests. Each model test has a model hypothesis followed by 2 experiments each with a different setting of the variable to be researched. Lastly the findings are reflected upon. The following research question will be reviewed in this chapter:

RQ 7. Do patterns emerge in the model?

8.1 Input parameters for the model:

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 total length of the rural road was 7.813km for 2019 and 5.458km for highway roads in the Netherlands (CBS, 2020). 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.

8.2 Model experiments

Each of the two experiments consists of a hypothesis, their model results and an analysis of those results.

8.2.1 Hypothesis 1

There are two hypotheses which are to be tested with the agent-based model. 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. So if the H_1 holds, the effects can also be translated to the introduction of AVs. Meaning that a larger penetration rate of AVs will have a safety benefit on Dutch rural roads. The hypotheses are as follows:

H_0 = The death count of vehicles and mean headway of vehicles on rural roads will not increase with the speed heterogeneity of HDVs.

H_1 = The death count of vehicles and mean headway of vehicles on rural roads will increase with the speed heterogeneity of HDVs.

8.2.2 Model results simulation 1

To accommodate the hypothesis two model experiments are run for this hypothesis. The 1st simulation is set with heterogeneity at 30, speed limit at 60 km/h and speed excess in order to overtake at 25, 1 truck, 2 AVs and 4 HDVs. The 2nd simulation is set with heterogeneity at 15 and speed excess in order to overtake at 25, 1 truck, 2 AVs and 4 HDVs. The 1st simulation results are depicted on the left and the 2nd on the right. The mean headway of vehicles over 50 model runs * 100 ticks = 50.000 results. First, a sorted vector of the mean headway over time is displayed below to show the frequency of headways which are encountered over the model runs in time. The frequencies of headways are nearly identical among the two experiments, there is a slight difference in the bottom right corner on the vectors but on closer inspection this is due to the scaling of the graphs. It can be concluded that the amount of times a certain headway is encountered in the model runs is similar among both experiments.

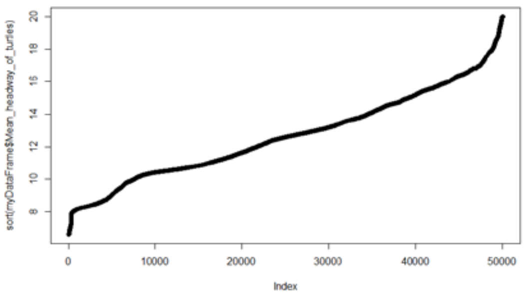

Figure 17: Sorted vector experiment 1

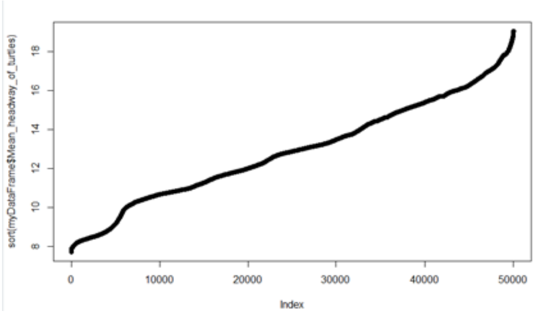

Figure 18: Sorted vector experiment 2

8.2.3 Analysis

The colored plots of model runs do show differences in model behavior for the model runs. It can be seen in figure 19 that the mean headways have more diffuse and irregular behavior than figure 20.

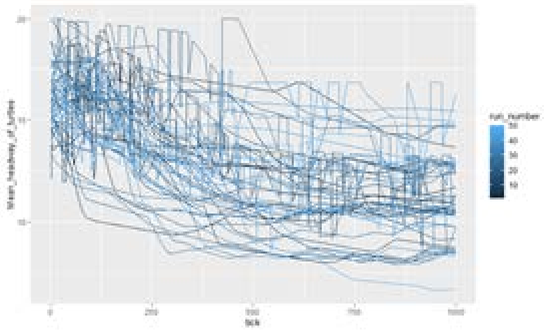

Figure 19: Plot of model runs - mean headway experiment 1

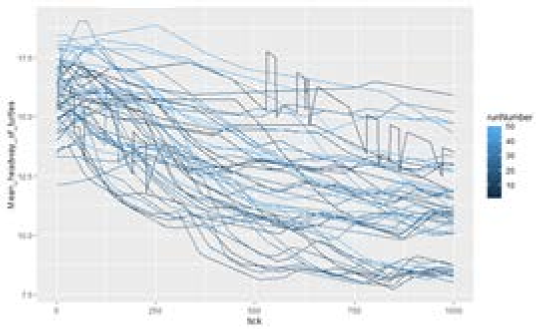

Figure 20: Plot of model runs - mean headway experiment 2

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 19 and 20. Figure 19 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 20 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 in which there would have to be 2 HDVs on the same lane with a difference in actual speed of 25. In figure 20 it can be seen this happens in 2 of the 50 model runs.

Table 5: Statistics of output variables simulation 1, experiment 1

	Mean headway of turtles	Death count
Min.	6.613	0.000
1st Quartile	10.607	0.000
Median	12.596	0.000
Mean	12.664	0.183
3rd Quartile	14.665	0.000
Max.	20.000	4.000

Table 6: Statistics of output variables simulation 1, experiment 2

	Mean headway of turtles	Death count
Min.	7.712	0.000
1st Quartile	10.906	0.000
Median	12.876	0.000
Mean	12.898	0.037
3rd Quartile	15.001	0.000
Max.	19.057	2.000

In the statistics in table 5 and 6 it can be seen that the mean headway is larger in the second experiment but the maximum headway is lower in the second experiment than in the first. No visible conclusions can be drawn that safety increases with headway as it is quite similar across both experiments which can be seen in figure 21 and 22. The boxplots in figure 21 and 22 translate to tables 5 and 6 respectively. It can be concluded in table 5 and 6 above that the death count is significantly lower in table 6 when the speed heterogeneity of HDVs is halved in the second simulation. When speed-heterogeneity halves, the amount of deaths decline with 79,8%. It is concluded the death count of vehicles will decline with speed heterogeneity of HDVs. This in turn can be generalized to the introduction of AVs as they will reduce speed heterogeneity in traffic, so the introduction of AVs will lead to fewer traffic deaths.

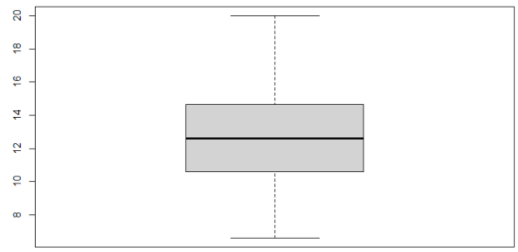

Figure 21: Boxplot mean headway experiment 1

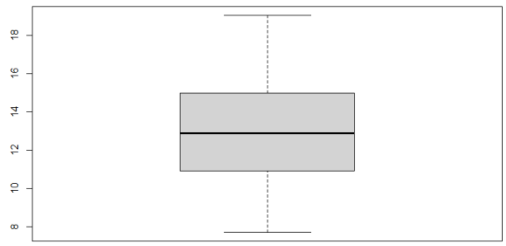

Figure 22: Boxplot mean headway experiment 2

8.2.4 Hypothesis 2

In section 1.2.1 it was concluded that autonomous vehicles are more efficient in traffic, this is because they can safely achieve a smaller headway and therefore more vehicles can be put on the same section of road. Therefore 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. Hypotheses are made to test whether this headway correlates with death count with an increased percentage of AVs. The two hypotheses are as follows:

H_0 = An increased percentage of AVs will not affect the mean headway of AVs and death count.

H_1 = An increased percentage of AVs will cause a reduced mean headway of AVs and death count.

8.2.5 Model results simulation 2

To suit the hypothesis two model experiments are run for this hypothesis. The 1st simulation is set with heterogeneity at 15, speed limit at 80 km/h and speed excess in order to overtake at 25 with 1 truck, 2 AVs and 4 HDVs. The 2nd simulation is set with heterogeneity at 15, speed limit at 80 km/h and speed excess in order to overtake at 25, 1 truck, but now with 4 AVs and 2 HDVs. The 1st simulation results are depicted on the left hand side and the second on the right hand side.

This second simulation also makes use of 50 model runs * 100 ticks = 50.000. First, a sorted vector of the mean headway of all vehicles over time is displayed below in figure 23 and 24 to show the frequency of headways for all vehicles which are encountered. These also show little difference.

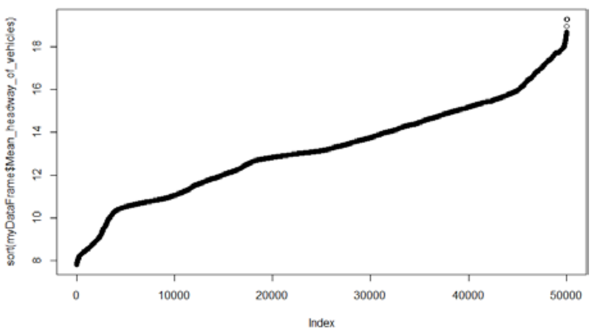

Figure 23: Sorted vector experiment 1 – mean headway of all vehicles

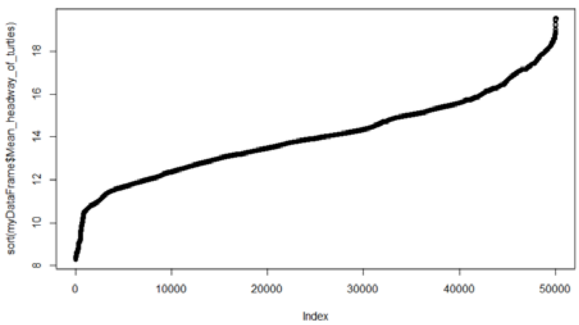

Figure 24 : Sorted vector experiment 2 – mean headway of all vehicles

8.2.6 Analysis

The sorted vectors of mean headway of all vehicles do not show much difference in figure 23 and 24. The sorted vectors of headway of AVs in figure 25 and figure 26 do however.

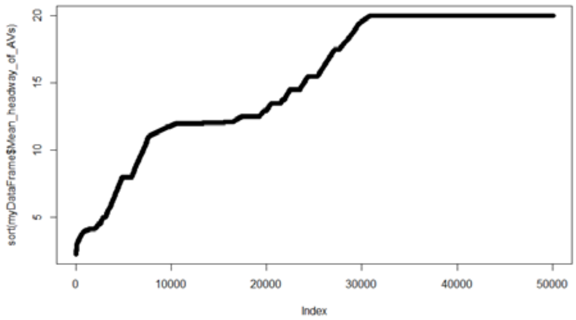

Figure 25: Sorted vector experiment 1 – headway of AVs

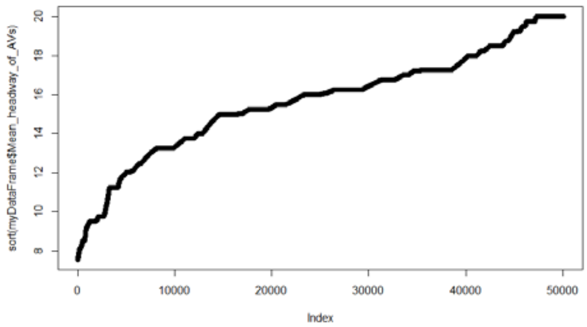

Figure 26: Sorted vector experiment 2 - headway of AVs

The line in figure 26 climbs up sooner but ascends to the top later. This can also be seen in table 8 as the 1st quartile is higher for mean headway of AVs in table 8 than table 7 and the third quartile is lower in table 8 than table 7 for mean headway of vehicles. This shows that an increased percentage of AVs will result in an average higher headway of AVs but fewer AVs with a higher headway. In the model runs it can be seen that in the first experiment with more HDVs, AVs would often hold up the other HDVs resulting in a large headway in front of them. With fewer HDVs in experiment 2 this phenomenon was experienced to a lesser extent. The model results show that the model is very path dependent. The creation of the vehicles on a certain place on a certain lane determine model behavior for a great deal but conclusions can still be drawn from the data.

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.

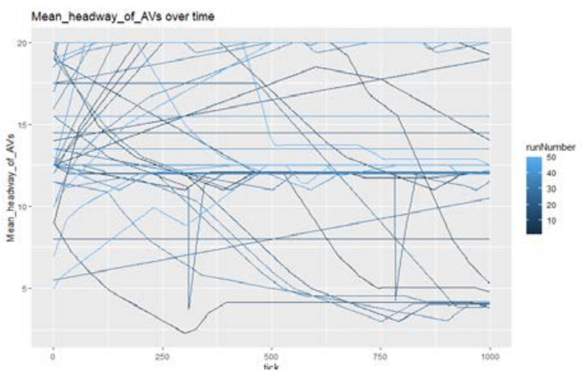

Figure 27: Plot of model runs - mean headway experiment 1

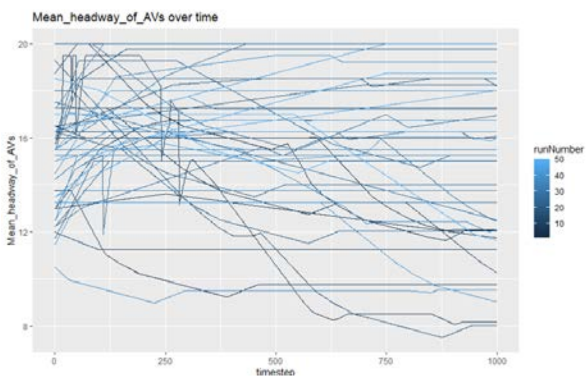

Figure 28: Plot of model runs - mean headway experiment 2

The plots of model runs in figure 28 show less heterogeneous headways than in figure 27, 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.

Table 7: Statistics of output variables simulation 2, experiment 1

	Mean headway of vehicles	Mean headway of AVs	Death count
Min.	7.81	2.26	0
1st Quartile	11.6	12.00	0
Median	13.15	15.50	0
Mean	13.22	15.14	0
3rd Quartile	14.86	20	0
Max.	19.29	20	0

There are zero deaths reported. This seems logical because the speed excess in order to overtake must be 25. It requires for one HDV to have a very low speed at the end of the spectrum so 65, 66, 67, 68, 69 or 70 and for another HDV to have a very high speed of 90, 91, 92, 93, 94 or 95 respectively. Furthermore the HDVs would have to be at the same lane with the overtaking HDV without any traffic in front of it as it would otherwise not attempt the overtaking maneuver. The low possibility of overtakes explains the non-existent death count.

Table 8: Statistics of output variables simulation 2, experiment 2

	Mean headway of vehicles	Mean headway of AVs	Death count
Min.	8.31	7.52	0
1st Quartile	12.71	14.02	0
Median	13.94	16.02	0
Mean	14.03	15.66	0
3rd Quartile	15.32	17.25	0
Max.	19.52	20	0

8.3 Conclusion

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. It is concluded that the death count decreases with a decrease in speed heterogeneity of HDVs.

In the second simulation hypothesis H_1 is rejected: an increased percentage of AVs actually causes the mean headway of AVs to increase. This is in turn another path dependency of the model. Because the speed of AVs is set the same they do not group together, the place on the road where the AV is put determines their distance to one another. A last remark is that deaths in the model only come in pairs of two or four as vehicles have to bump in to each other.

Chapter 9: Conclusion & discussion

This chapter concludes the master thesis. First the conclusions from the previous chapter are shortly stated and a discussion is held. Secondly there is a discussion where the weakness of the current modeling method is given and it is explained how further research can build upon the findings of this thesis. Lastly societal relevance is discussed and recommendations are given in section 9.3.

9.1 Conclusions

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. So how do these two conclusions relate to the main research question stated below?

MQ: What are the effects of the transition phase from HDVs to AVs in the Netherlands for traffic safety on rural roads?

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.

9.2 Discussion

The scientific literature used in the literature study chapters 1, 2 and 3 mainly found in transport and psychology journals. This is logical because driving behavior of HDVs is largely determined through human psychology. There are also several papers with equation modeling techniques to be found in transport literature but these are scarcely used as the described technique did not align with the agent-based modeling approach. Several classic literature sources have been used to model HDV behavior.

9.2.1 Perspective

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.

9.2.2 Critical analysis of findings

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.

9.2.3 Limitations of the study

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.

Assumptions are made which could be argued but these assumptions are made with reasoning and it is thereby taken into account and stated what these assumptions would mean for the behavior of the model. A simplification is made that when two vehicles touch they both die, where in the real world there could also be accidents. Traditional safety statistics report accidents as well as casualties. In order to not draw an arbitrary line when it would be an accident or when it would be a casualty and to keep the model not overly complex, a simplification was made to just report casualties. Both forms are unwanted side effects of transport movements so could be grouped together.

9.2.4 Future directions

The model could be 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.

9.3 Societal relevance & recommendations

The conclusions in section 9.1 are related to the main research question but the main societal effects on the implementation of AVs are not stated yet. 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.

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Appendix A: Pseudo-code mode l formalization

-Ask vehicle in front its speed, set the speed-vehicle-in-front according to this speed
-Set headway equal to coordinate B (location vehicle in front) – coordinate A (your own location)
-If there is a junction in sight set junction-coming true else set junction-coming false
-Set overtaking-space equal to coordinate C (location vehicle in front of vehicle in front) - coordinate B (location vehicle in front)
-If there is room on opposite lane (coordinate D (location vehicle on opposite lane) – coordinate A (your own location) >= value X)
set room-overtaking lane true else set room-overtaking false
-If driving on a lane with right-of-way set right-of way true else set right of way false
-If right of way = false check if there is room on lanes to cross

(To perceive own entities)
-Ask vehicle show actual speed
-Ask vehicle set frustration (frustration + (if desired speed – actual speed > 0 (desired speed - actual speed) else (0)))
-Ask vehicle check maximum speed limit

(Drives)
Ask vehicle if (desired speed – actual speed > 0) and (headway > value Y) or (overtaking = true) set actual speed (actual speed + Z)
Ask vehicle if (speed vehicle in front – actual speed < 0) and (headway < value Y) and (overtaking = false) set actual speed (actual speed – Z)
Ask HDVs if ((frustration > F) and (actual speed - speed vehicle in front > value L) and ((size vehicle in front + headway in front) > value S) and room overtaking = true and junction coming = false) set overtaking true turn onto opposing lane
if Y-coordinate > value G set turn straight
if vehicle in front is passed set overtake = false and turn back
if y coordinate < value J set turn straight
Ask HDVs if overtake = true and (junction-coming true or room-overtaking = false) set overtaking false decelerate and turn back
Ask vehicles if junction coming = true and right of way = false and traffic clear = false stop
Ask vehicles move forward actual speed

Appendix B: Model code

```
breed [ AVs AV ]
breed [ CVs CV ]
breed [ Trucks truck ]

globals [ initial-vehicles      ;; states the initial number of vehicles
        timestep                  ]

turtles-own [             ;; General turtle (vehicle) properties
          speed                 ;; actual speed of the agents
          target-speed           ;; what speed agent wants to drive, set in the setup and not altered after
          speed-vehicle-in-front   ;; speed of the vehicle in front
          headway-vehicle-in-front ;; headway of the vehicle in front
          headway                ;; distance to vehicle in front
          right-of-way           ;; right of way on the lane or not
          junction1-in-sight      ;; nearing junction 1 or not
          junction2-in-sight      ;; nearing junction 2 or not
          traffic               ;; only relevant for agent with heading 0 (on intersection) if there is
conflicting traffic
          cross-road            ;; if it is safe for the agent with heading 0 (on intersection) to cross the
road
]

CVs-own  [               ;; CV specific properties relating to overtaking
           frustration           ;; frustration level of agent, increased when desired speed is lower than
current speed
           room-ahead            ;; room ahead on the lane it is in
           oncoming-traffic       ;; if there is traffic from the opposite lane
           free-to-overtake       ;; if there is no traffic from the opposite lane there is room to overtake
           perform-overtake       ;; actually performing overtake true false
           return                ;; an on/off for returning to the lane with the correct heading after
overtaking
           traffic-beside-me      ;; if the vehicle can return to its lane, if there is space
           room-to-return        ;;
           room-overtakers ]      ;;

to setup                 ;; setup conditions
  clear-all
  set-default-shape turtles "car"
  make-road
  vehicle-distribution
  reset-ticks
  set timestep 0 ;;
end

to drive                 ;; Actual moving forward, observing and dying
  perceive
  move-forward
  die-if-accident
```

```
  tick
  set timestep (timestep + 1)
end

to perceive              ;; Observe different properties necessary for driving
  ask turtles [ note-speed
             note-headway
             note-headway-vehicle-in-front
             observe-junctions
             note-right-of-way
             note-room-to-cross
              ]
  ask CVs    [ note-frustration
             note-perform-overtake
  ]
  note-room-opposite-lane
  note-room-ahead
  note-room-return
end

to note-speed            ;; Note the speed of the vehicle that is in front otherwise hold a reference value of its own speed
  ifelse any? turtles-on patch-ahead 15 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 15 ] [ set speed-vehicle-in-front speed ]
         if    any? turtles-on patch-ahead 14 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 14 ]
         if    any? turtles-on patch-ahead 13 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 13 ]
         if    any? turtles-on patch-ahead 12 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 12 ]
         if    any? turtles-on patch-ahead 11 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 11 ]
         if    any? turtles-on patch-ahead 10 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 10 ]
         if    any? turtles-on patch-ahead 9 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 9 ]
         if    any? turtles-on patch-ahead 8 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 8 ]
         if    any? turtles-on patch-ahead 7 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 7 ]
         if    any? turtles-on patch-ahead 6 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 6 ]
         if    any? turtles-on patch-ahead 5 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 5 ]
         if    any? turtles-on patch-ahead 4 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 4 ]
         if    any? turtles-on patch-ahead 3 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 3 ]
         if    any? turtles-on patch-ahead 2 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 2 ]
         if    any? turtles-on patch-ahead 1 [ set speed-vehicle-in-front [speed] of one-of turtles-on patch-ahead 1 ]
```

```
end

to note-headway-vehicle-in-front      ;; Note the headway of the vehicle that is in front otherwise hold
a reference value of 20
   ifelse any? turtles-on patch-ahead 15 [ set headway-vehicle-in-front [headway] of one-of turtles-on
patch-ahead 15 ] [ set headway-vehicle-in-front 20 ]
            if    any? turtles-on patch-ahead 14 [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 14 ]
            if    any? turtles-on patch-ahead 13 [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 13 ]
            if    any? turtles-on patch-ahead 12 [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 12 ]
            if    any? turtles-on patch-ahead 11 [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 11 ]
            if    any? turtles-on patch-ahead 10 [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 10 ]
            if    any? turtles-on patch-ahead 9  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 9 ]
            if    any? turtles-on patch-ahead 8  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 8 ]
            if    any? turtles-on patch-ahead 7  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 7 ]
            if    any? turtles-on patch-ahead 6  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 6 ]
            if    any? turtles-on patch-ahead 5  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 5 ]
            if    any? turtles-on patch-ahead 4  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 4 ]
            if    any? turtles-on patch-ahead 3  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 3 ]
            if    any? turtles-on patch-ahead 2  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 2 ]
            if    any? turtles-on patch-ahead 1  [ set headway-vehicle-in-front [headway] of one-of
turtles-on patch-ahead 1 ]
end

to note-headway           ;; Note the headway of the vehicle that is in front for all vehicles

  if heading = 90 [
;; Headway
            ifelse any? turtles-on patch-ahead 20 [ set headway ([xcor] of one-of turtles-on patch-ahead
20 + 50 - ([xcor] of one-of turtles-here + 50)) ] [ set headway 20] ;; Note the headway to the vehicle
that is in front for vehicles with heading to the left
            if    any? turtles-on patch-ahead 19 [ set headway ([xcor] of one-of turtles-on patch-ahead
19 + 50 - ([xcor] of one-of turtles-here + 50))   ]              ;; The + 50 is so that all patches are 0 to 100
instead of -50 to 50, easier to calculate
            if    any? turtles-on patch-ahead 18 [ set headway ([xcor] of one-of turtles-on patch-ahead
18 + 50 - ([xcor] of one-of turtles-here + 50))   ]
            if    any? turtles-on patch-ahead 17 [ set headway ([xcor] of one-of turtles-on patch-ahead
17 + 50 - ([xcor] of one-of turtles-here + 50))   ]
            if    any? turtles-on patch-ahead 16 [ set headway ([xcor] of one-of turtles-on patch-ahead
16 + 50 - ([xcor] of one-of turtles-here + 50))   ]
```

```
        if   any? turtles-on patch-ahead 15 [ set headway ([xcor] of one-of turtles-on patch-ahead
15 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 14 [ set headway ([xcor] of one-of turtles-on patch-ahead
14 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 13 [ set headway ([xcor] of one-of turtles-on patch-ahead
13 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 12 [ set headway ([xcor] of one-of turtles-on patch-ahead
12 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 11 [ set headway ([xcor] of one-of turtles-on patch-ahead
11 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 10 [ set headway ([xcor] of one-of turtles-on patch-ahead
10 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 9  [ set headway ([xcor] of one-of turtles-on patch-ahead  9
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 8  [ set headway ([xcor] of one-of turtles-on patch-ahead  8
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 7  [ set headway ([xcor] of one-of turtles-on patch-ahead  7
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 6  [ set headway ([xcor] of one-of turtles-on patch-ahead  6
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 5  [ set headway ([xcor] of one-of turtles-on patch-ahead  5
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 4  [ set headway ([xcor] of one-of turtles-on patch-ahead  4
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 3  [ set headway ([xcor] of one-of turtles-on patch-ahead  3
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 2  [ set headway ([xcor] of one-of turtles-on patch-ahead  2
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 1  [ set headway ([xcor] of one-of turtles-on patch-ahead  1
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
  if headway < 0 [ set headway (headway + 101) ] if headway > 20 [ set headway 20 ]]   ;; correction
for large negative value due to wrapping of the edges of the world
 if heading = 270 [
        ifelse any? turtles-on patch-ahead 20 [ set headway ([xcor] of one-of turtles-on patch-ahead
20 + 50 - ([xcor] of one-of turtles-here + 50)) ] [ set headway 20] ;; Note the headway to the vehicle
that is in front for vehicles with heading to the right
        if   any? turtles-on patch-ahead 19 [ set headway ([xcor] of one-of turtles-on patch-ahead
19 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 18 [ set headway ([xcor] of one-of turtles-on patch-ahead
18 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 17 [ set headway ([xcor] of one-of turtles-on patch-ahead
17 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 16 [ set headway ([xcor] of one-of turtles-on patch-ahead
16 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 15 [ set headway ([xcor] of one-of turtles-on patch-ahead
15 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 14 [ set headway ([xcor] of one-of turtles-on patch-ahead
14 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 13 [ set headway ([xcor] of one-of turtles-on patch-ahead
13 + 50 - ([xcor] of one-of turtles-here + 50))   ]
        if   any? turtles-on patch-ahead 12 [ set headway ([xcor] of one-of turtles-on patch-ahead
12 + 50 - ([xcor] of one-of turtles-here + 50))   ]
```

```
            if     any? turtles-on patch-ahead 11 [ set headway ([xcor] of one-of turtles-on patch-ahead
11 + 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 10 [ set headway ([xcor] of one-of turtles-on patch-ahead
10 + 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 9  [ set headway ([xcor] of one-of turtles-on patch-ahead  9
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 8  [ set headway ([xcor] of one-of turtles-on patch-ahead  8
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 7  [ set headway ([xcor] of one-of turtles-on patch-ahead  7
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 6  [ set headway ([xcor] of one-of turtles-on patch-ahead  6
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 5  [ set headway ([xcor] of one-of turtles-on patch-ahead  5
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 4  [ set headway ([xcor] of one-of turtles-on patch-ahead  4
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 3  [ set headway ([xcor] of one-of turtles-on patch-ahead  3
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 2  [ set headway ([xcor] of one-of turtles-on patch-ahead  2
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if     any? turtles-on patch-ahead 1  [ set headway ([xcor] of one-of turtles-on patch-ahead  1
+ 50 - ([xcor] of one-of turtles-here + 50))   ]
            if headway < 0 [ set headway (headway * -1) ]              ;; correction for opposite heading
            if headway > 20 [ set headway ((headway * -1) + 101)  ] if headway > 20 [ set headway 20 ] ]
;; correction for large negative value due to wrapping of the edges of the world

  if heading = 0 [ set headway mean [headway] of turtles ] ;; In order not to influence results,
headway of crossing traffic is set to the average

end

to observe-junctions       ;; Observe if there are junctions or not
   if Intersection-1 = true [
    if heading = 90  and ([xcor] of one-of turtles-here >= -17 - vision and [xcor] of one-of turtles-here
<= -12 )[ set junction1-in-sight true  ]   ;; condition for position on road where vehicle can see junction
    if heading = 90  and ([xcor] of one-of turtles-here >= -12) [ set junction1-in-sight false ]
;; when past the junction on the right set false
    if heading = 90  and ([xcor] of one-of turtles-here <= -17 - vision ) [ set junction1-in-sight false ]
;; when too far beyond vision before junction set false
    if heading = 270 and ([xcor] of one-of turtles-here >= -17 and [xcor] of one-of turtles-here <= -12 +
vision )[ set junction1-in-sight true  ]   ;; condition for position on road where vehicle can see junction
    if heading = 270 and ([xcor] of one-of turtles-here <= -17) [ set junction1-in-sight false ]
;; when past the junction on the left set false
    if heading = 270 and ([xcor] of one-of turtles-here >= -12 + vision ) [ set junction1-in-sight false ] ]
;; when too far beyond vision before junction set false
  if Intersection-2 = true [
    if heading = 90  and ([xcor] of one-of turtles-here >= 20 - vision and [xcor] of one-of turtles-here <=
25 )[ set junction2-in-sight true  ]     ;; condition for position on road where vehicle can see junction
    if heading = 90  and ([xcor] of one-of turtles-here >= 25) [ set junction2-in-sight false ]
;; when past the junction on the right set false
    if heading = 90  and ([xcor] of one-of turtles-here <= 20 - vision ) [ set junction2-in-sight false ]
;; when too far beyond vision before junction set false
```

```
   if heading = 270 and ([xcor] of one-of turtles-here >= 20 and [xcor] of one-of turtles-here <= 25 +
vision )[ set junction2-in-sight true  ]     ;; condition for position on road where vehicle can see
junction
   if heading = 270 and ([xcor] of one-of turtles-here <= 20) [ set junction2-in-sight false ]
;; when past the junction on the left set false
   if heading = 270 and ([xcor] of one-of turtles-here >= 25 + vision ) [ set junction2-in-sight false ] ]
;; when too far beyond vision before junction set false
end

to note-right-of-way       ;; Does agent have right of way or not?
  ifelse heading = 0 [ set right-of-way false ] [set right-of-way true ]
end

to note-room-to-cross      ;; if there is room to cross the intersection
   set cross-road true
   set traffic other turtles in-cone side-vision angle-of-vision          ;; side-vision relates to how far
ahead it can see, angle-of vision on how far to the side it can see, its angle
   if any? traffic [ set cross-road false ]
end

to note-frustration        ;; CVs become frustrated if they can not achieve their target speed
  ifelse (target-speed - speed > 0 ) [ set frustration ( frustration + (target-speed - speed ) ) ] [ set
frustration 0 ]
  if frustration < 0 [ set frustration 0 ]
  end

to note-room-opposite-lane  ;; Observe if there is room to overtake on the opposite lane
  ask CVs with [ heading = 90   ]  [ set oncoming-traffic other turtles with [ heading = 270 and ycor > -5
and ycor < 5  ] in-cone vision-other-lane 90 ]  ;;
  ask CVs with [ heading = 270  ]  [ set oncoming-traffic other turtles with [ heading = 90  and ycor < 5
and ycor > -5 ] in-cone vision-other-lane 90 ]  ;;
  ask CVs with [ heading = 90 or heading = 270 ]  [ ifelse any? oncoming-traffic [ set free-to-overtake
false ] [ ifelse room-overtakers = true [ set free-to-overtake true ] [ set free-to-overtake false ]] ]
end

to note-room-return        ;; Observe if there is room to return on the original lane
  ask CVs with [ heading = 90 ]  [ set traffic-beside-me other turtles with [ heading = 90 and ycor = -2.5
] in-cone 12 180 ]
  ask CVs with [ heading = 90 ]  [ ifelse any? traffic-beside-me [ set room-to-return false ] [ set room-
to-return true set perform-overtake false ] ]
  ask CVs with [ heading = 90 ]  [ ifelse any? traffic-beside-me with [ heading = 270 ] [ set room-
overtakers false ] [ set room-overtakers true ] ]
  ask CVs with [ heading = 90 ] [ if (perform-overtake = false and ycor > -2.5)  [set room-to-return true
]  ]

  ask CVs with [ heading = 270 ] [ set traffic-beside-me other turtles with [ heading = 270 and ycor =
2.5  ] in-cone 12 180 ]
  ask CVs with [ heading = 270 ] [ ifelse any? traffic-beside-me [ set room-to-return false ] [ set room-
to-return true set perform-overtake false] ]
  ask CVs with [ heading = 270 ]  [ ifelse any? traffic-beside-me with [ heading = 90 ] [ set room-
overtakers false ] [ set room-overtakers true ] ]
```

```
  ask CVs with [ heading = 270 ] [ if (perform-overtake = false and ycor < 2.5)  [set room-to-return true
]  ]

end

to note-room-ahead         ;; Room ahead is equal to headway of self + headway of vehicle in front
  ask CVs [ set room-ahead (headway + headway-vehicle-in-front) ]
end

to note-perform-overtake    ;; If certain conditions are met (only a CV) perform an overtake
  if ( frustration > 500 ) and ( junction1-in-sight = false or junction1-in-sight = 0 ) and ( junction2-in-
sight = false or junction2-in-sight = 0 ) and (target-speed - speed-vehicle-in-front > speed-excess-to-
vehicle-in-front) and (room-ahead > 20 ) and (free-to-overtake = true) [ set perform-overtake true ]
  if ( flying-overtake   ) and ( junction1-in-sight = false or junction1-in-sight = 0 ) and ( junction2-in-
sight = false or junction2-in-sight = 0 ) and (target-speed - speed-vehicle-in-front > speed-excess-to-
vehicle-in-front) and (room-ahead > 20 ) and (free-to-overtake = true) [ set perform-overtake true ]
end

to move-forward           ;; determine correct speed and decelerate of accelerate depending on that
condition
  accelerate
  decelerate
  ask turtles [ if speed < 0 [ set speed 0 ] ]               ;; Turtles are not meant to drive backwards
  ask turtles [ if heading != 0     [ fd ( speed / 100 ) ]   ]                   ;; Move forward according to their
speed
  ask turtles [ if heading = 0 and cross-road = true  [ fd ( speed / 100 ) ] ]
  ask turtles [ if heading = 0 and cross-road = false [ if ycor < -8.5 [  fd ( speed / 100 )  ] ]] ;; If the
crossing maneuver has started dont stop on the intersection itself
  ask turtles [ if heading = 0 and cross-road = false [ if ycor > -7.5 [  fd ( speed / 100 )  ] ]] ;; If the
crossing maneuver has started dont stop on the intersection itself
end

to die-if-accident         ;; Vehicles die if they come into contact with other vehicles
  ask turtles [ if any? other turtles in-radius 1.5 [  ask other turtles in-radius 1.5  [ die  ]  die   ]]
end

to accelerate             ;; set speed higher if certain conditions are met
  ask CVs with [ perform-overtake = false ]   [ if headway >= 4 and speed < target-speed and speed < (
speed-vehicle-in-front + 1 ) [ set speed ( speed + 0.5 ) ] ]  ;; accelerate when there is sufficient room

  ;; Overtaking for vehicles on bottom-lane
  ask CVs with [ perform-overtake = true and heading = 90 and return = false  ]   [ set speed ( speed +
2) if ycor <= 2.5  [ set ycor (ycor + 0.75)  ] ]
  ask CVs with [ heading = 90  and ycor > 2.5   ] [ set ycor  2.5 ]                         ;; Vehicles cannot
exceed upper bound
  ask CVs with [ heading = 90  and ycor > 0 and room-to-return = true ]  [ set return true ]   ;; If vehicle
can return after passing it will do so
  ask CVs with [ heading = 90  and return = true ] [ set ycor (ycor - 0.5)  ]          ;; Descend if there is
room
  ask CVs with [ heading = 90  and ycor < -2.5 ] [ set return false set ycor -2.5 set perform-overtake
false ]           ;; Vehicles with a heading to the right can not move horizontally below their own lane
  ask CVs with [ heading = 90  and ycor = -2.5 ] [ set return false set ycor -2.5  ]
```

```
  ask CVs with [ heading = 90  and (ycor > -2.5) and perform-overtake = false ] [ set return true ]


  ;; Overtaking for vehicles on top-lane
  ask CVs with [ perform-overtake = true and heading = 270 and return = false  ]   [ set speed ( speed +
2) if ycor >= -2.5  [ set ycor (ycor - 0.75)  ] ]
  ask CVs with [ heading = 270  and ycor < -2.5   ] [ set ycor  -2.5 ]                          ;; Vehicles cannot
exceed upper bound
  ask CVs with [ heading = 270  and ycor < 0 and room-to-return = true ]  [ set return true ]   ;; If
vehicle can return after passing it will do so
  ask CVs with [ heading = 270  and return = true  ] [ set ycor (ycor + 0.5) set frustration 0 ]           ;;
Descend if there is room
  ask CVs with [ heading = 270  and ycor > 2.5 ] [ set return false set ycor 2.5 set perform-overtake
false ]            ;; Vehicles with a heading to the right can not move horizontally below their own lane
  ask CVs with [ heading = 270  and ycor = 2.5 ] [ set return false set ycor 2.5 ]
  ask CVs with [ heading = 270  and (ycor < 2.5) and perform-overtake = false ] [ set return true ]

  ask CVs with [ heading = 90 or heading = 270 ][ if headway > 8 [ set frustration 0 ]]

  ask CVs    [ if ( speed > target-speed) and ( perform-overtake = false ) [ set speed ( speed - 0.5 ) ] ] ;;
vehicle cannot accelerate past its maximum speed except when overtaking

  ask Trucks [ if headway >= 4 and speed < target-speed and speed < speed-vehicle-in-front [ set
speed ( speed + 0.5 ) ] ]  ;; accelerate when there is sufficient room
  ask Trucks [ if speed > target-speed [ set speed ( speed - 0.5 ) ] ] ;; vehicle cannot accelerate past its
maximum speed

  ask AVs    [ if headway >= 4 and speed < target-speed and speed < speed-vehicle-in-front [ set speed
( speed + 0.5 ) ] ]  ;; accelerate when there is sufficient room
  ask AVs    [ if speed > target-speed [ set speed ( speed - 0.5 ) ] ] ;; vehicle cannot accelerate past its
maximum speed
end

to decelerate             ;; Set speed lower if certain conditions are met
  ask CVs [ if headway >= 9    and headway < 10   and ( speed - speed-vehicle-in-front) > 5  and (
perform-overtake = false ) [ set speed ( speed - 1.5) ] ]  ;; decelerate when vehicle in front
  ask CVs [ if headway >= 8    and headway < 9    and ( speed - speed-vehicle-in-front) > 5  and (
perform-overtake = false ) [ set speed ( speed - 1.5) ] ]
  ask CVs [ if headway >= 7    and headway < 8    and ( speed - speed-vehicle-in-front) > 4  and (
perform-overtake = false ) [ set speed ( speed - 1.5) ] ]
  ask CVs [ if headway >= 6    and headway < 7    and ( speed - speed-vehicle-in-front) > 4  and (
perform-overtake = false ) [ set speed ( speed - 2.5) ] ]
  ask CVs [ if headway >= 5    and headway < 6    and ( speed - speed-vehicle-in-front) > 3  and (
perform-overtake = false ) [ set speed ( speed - 2.5) ] ]
  ask CVs [ if headway >= 4    and headway < 5    and ( speed - speed-vehicle-in-front) > 3  and (
perform-overtake = false ) [ set speed ( speed - 2.5) ] ]
  ask CVs [ if headway >= 3    and headway < 4    and ( speed - speed-vehicle-in-front) > 2  and (
perform-overtake = false ) [ set speed ( speed - 3.5) ] ]
  ask CVs [ if headway >= 2.5  and headway < 3    and ( speed - speed-vehicle-in-front) > 2  and (
perform-overtake = false ) [ set speed ( speed - 3.5) ] ]
  ask CVs [ if headway >= 2    and headway < 2.5  and ( speed - speed-vehicle-in-front) > 2  and (
perform-overtake = false ) [ set speed ( speed - 4.5) ] ]
```

```
  ask CVs [ if headway >= 1    and headway < 2    and ( speed - speed-vehicle-in-front) >= 0 and (
perform-overtake = false ) [ set speed ( speed - 5.5) ] ]

  ask Trucks [ if headway >= 9    and headway < 10   and ( speed - speed-vehicle-in-front) > 5  [ set
speed ( speed - 1.5) ] ]  ;; decelerate when vehicle in front
  ask Trucks [ if headway >= 8    and headway < 9    and ( speed - speed-vehicle-in-front) > 5  [ set
speed ( speed - 1.5) ] ]
  ask Trucks [ if headway >= 7    and headway < 8    and ( speed - speed-vehicle-in-front) > 4  [ set
speed ( speed - 1.5) ] ]
  ask Trucks [ if headway >= 6    and headway < 7    and ( speed - speed-vehicle-in-front) > 4  [ set
speed ( speed - 2.5) ] ]
  ask Trucks [ if headway >= 5    and headway < 6    and ( speed - speed-vehicle-in-front) > 3  [ set
speed ( speed - 2.5) ] ]
  ask Trucks [ if headway >= 4    and headway < 5    and ( speed - speed-vehicle-in-front) > 3  [ set
speed ( speed - 2.5) ] ]
  ask Trucks [ if headway >= 3    and headway < 4    and ( speed - speed-vehicle-in-front) > 2  [ set
speed ( speed - 3.5) ] ]
  ask Trucks [ if headway >= 2.5  and headway < 3    and ( speed - speed-vehicle-in-front) > 2  [ set
speed ( speed - 3.5) ] ]
  ask Trucks [ if headway >= 2    and headway < 2.5  and ( speed - speed-vehicle-in-front) > 2  [ set
speed ( speed - 4.5) ] ]
  ask Trucks [ if headway >= 1    and headway < 2    and ( speed - speed-vehicle-in-front) >= 0 [ set
speed ( speed - 5.5) ] ]

  ask AVs [ if headway >= 9    and headway < 10   and ( speed - speed-vehicle-in-front) > 5  [ set speed
( speed - 1) ] ]  ;; decelerate when vehicle in front
  ask AVs [ if headway >= 8    and headway < 9    and ( speed - speed-vehicle-in-front) > 5  [ set speed (
speed - 1) ] ]
  ask AVs [ if headway >= 7    and headway < 8    and ( speed - speed-vehicle-in-front) > 4  [ set speed (
speed - 1) ] ]
  ask AVs [ if headway >= 6    and headway < 7    and ( speed - speed-vehicle-in-front) > 4  [ set speed (
speed - 2) ] ]
  ask AVs [ if headway >= 5    and headway < 6    and ( speed - speed-vehicle-in-front) > 3  [ set speed (
speed - 2) ] ]
  ask AVs [ if headway >= 4    and headway < 5    and ( speed - speed-vehicle-in-front) > 3  [ set speed (
speed - 2) ] ]
  ask AVs [ if headway >= 3    and headway < 4    and ( speed - speed-vehicle-in-front) > 2  [ set speed (
speed - 3) ] ]
  ask AVs [ if headway >= 2.5  and headway < 3    and ( speed - speed-vehicle-in-front) > 2  [ set speed
( speed - 3) ] ]
  ask AVs [ if headway >= 2    and headway < 2.5  and ( speed - speed-vehicle-in-front) > 2  [ set speed
( speed - 4) ] ]
  ask AVs [ if headway >= 1    and headway < 2    and ( speed - speed-vehicle-in-front) >= 0 [ set speed
( speed - 5) ] ]
end

to vehicle-distribution     ;; Initial distribution of vehicles and their settings
  while [ count AVs != #AVs ] [ create-AVs 1 [ set heading 90 set size 2 set color yellow set xcor -50 +
random 100 set ycor -2.5 + random 6         ;; create AV with yellow color until there are of the set
amount
        if ycor > 0 [ set ycor 2.5  set heading 270 set shape "car-opposite" ]   if ycor < 0 [ set ycor -2.5 ]
;; if the switch with opposing traffic = on the heading of the top lane is the other way around
```

```
        while [ any? turtles-on patch-ahead -1 or any? turtles-on patch-ahead -2 or any? turtles-on
patch-ahead -3 or any? turtles-on patch-ahead -4 ;; create an AV and move away from the other
turtles, die if there is already an AV here
               or any? turtles-on patch-ahead 1 or any? turtles-on patch-ahead 2 or any? turtles-on patch-
ahead 3 or any? turtles-on patch-ahead 4
  ] [ fd 1 ] if any? other turtles-here [ die ] ]  ]

   while [ count CVs != #HDVs ] [ create-CVs 1 [ set heading 90 set size 2 set color red set xcor -50 +
random 100 set ycor -2.5 + random 6           ;; same as above with CVs
        if ycor > 0 [ set ycor 2.5  set heading 270 set shape "car-opposite" ]   if ycor < 0 [ set ycor -2.5 ]
        while [ any? turtles-on patch-ahead -1 or any? turtles-on patch-ahead -2 or any? turtles-on
patch-ahead -3 or any? turtles-on patch-ahead -4
               or any? turtles-on patch-ahead 1 or any? turtles-on patch-ahead 2 or any? turtles-on patch-
ahead 3 or any? turtles-on patch-ahead 4
  ] [ fd 1 ] if any? other turtles-here [ die ] ]  ]

  while [ count trucks != #trucks ] [ create-Trucks 1 [ set heading 90 set size 2 set color blue set xcor -
50 + random 100 set ycor -2.5 + random 6   ;; same as above with Trucks
        if ycor > 0 [ set ycor 2.5  set heading 270 set shape "car-opposite" ]   if ycor < 0 [ set ycor -2.5 ]
        while [ any? turtles-on patch-ahead -1 or any? turtles-on patch-ahead -2 or any? turtles-on
patch-ahead -3 or any? turtles-on patch-ahead -4
               or any? turtles-on patch-ahead 1 or any? turtles-on patch-ahead 2 or any? turtles-on patch-
ahead 3 or any? turtles-on patch-ahead 4
  ] [ fd 1 ] if any? other turtles-here [ die ] ] ]
  ask AVs    [ set speed max-speed              set target-speed speed ]   ;; AVs maintain a constant speed
safely under the limit
  ask CVs    [ set perform-overtake false set speed ( max-speed - ( random heterogeneity-speed-HDVs
) + (2 * ( random heterogeneity-speed-HDVs ))) set target-speed speed ]   ;; The drivers of CVs
fluctuate of speed
  ask trucks [ set speed max-speed + random 3       set target-speed speed ]   ;; Trucks maintain a
speed of the speed limit or just above, driving in the margin of not getting a speeding ticket but also
wanting to drive fast
  if Intersection-1 = true [ ask one-of turtles [ set heading 0 set shape "car-up" set xcor -14.5 set ycor -
29 ] ]
  if Intersection-2 = true [ ask one-of turtles with [ ycor > -25] [ set heading 0 set shape "car-up" set
xcor  22.5 set ycor -29 ] ]   ;; with y-cor > -25 ensures that the vehicle from intersection is not taken to
intersection 2
  ask CVs [ set frustration 0 set return false ]
  perceive
  set initial-vehicles count turtles
end

to make-road               ;; build the main road and the environment
  ask patches [ set pcolor 56 ]                                   ;; display grass
  ask patches with [ pycor > -5 and pycor < 5 ]  [ set pcolor grey ]    ;; make main road asphalt
  ask patches with [ pycor = -5 or pycor = 5 or pycor = 0 and pxcor > -61 ] [ set pcolor white ]   ;; white
line on the sides of the road
  ask patches with [ pycor = 0 and pxcor > -47 and pxcor < -41 ] [ set pcolor grey ]   ;; white middle line
  ask patches with [ pycor = 0 and pxcor > -37 and pxcor < -31 ] [ set pcolor grey ]   ;; white middle line
  ask patches with [ pycor = 0 and pxcor > -27 and pxcor < -21 ] [ set pcolor grey ]   ;; white middle line
  ask patches with [ pycor = 0 and pxcor > -17 and pxcor < -11 ] [ set pcolor grey ]   ;; white middle line
  ask patches with [ pycor = 0 and pxcor > -7 and pxcor < 0 ] [ set pcolor grey ]      ;; white middle line
```

```
  ask patches with [ pycor = 0 and pxcor > 4 and pxcor < 10 ] [ set pcolor grey ]      ;; white middle line
  ask patches with [ pycor = 0 and pxcor > 14 and pxcor < 20 ] [ set pcolor grey ]     ;; white middle line
  ask patches with [ pycor = 0 and pxcor > 24 and pxcor < 30 ] [ set pcolor grey ]     ;; white middle line
  ask patches with [ pycor = 0 and pxcor > 34 and pxcor < 40 ] [ set pcolor grey ]     ;; white middle line
  ask patches with [ pycor = 0 and pxcor > 44 and pxcor < 50 ] [ set pcolor grey ]     ;; white middle line
  if intersection-1 [ first-junction ]
  if intersection-2 [ second-junction ]
end

to first-junction          ;; Display of the first junction with the patches
  ask patches with [ pxcor < -12 and pxcor > -17 and pycor > 4 ]  [ set pcolor grey ]    ;; Upper vertical
road first junction
  ask patches with [ pxcor < -12 and pxcor > -17 and pycor < -4]  [ set pcolor grey ]    ;; Bottom vertical
road first junction
  ask patches with [ pxcor = -12 and pycor > 5]  [ set pcolor white ]              ;; White line Upper left
  ask patches with [ pxcor = -12 and pycor < -5] [ set pcolor white ]              ;; White line Bottom left
  ask patches with [ pxcor = -17 and pycor > 5]  [ set pcolor white ]              ;; White line Upper right
  ask patches with [ pxcor = -17 and pycor < -5] [ set pcolor white ]              ;; White line Bottom right
end

to second-junction         ;; Display of the second junction with the patches
  ask patches with [ pxcor > 20 and pxcor < 25 and pycor > 4 ]  [ set pcolor grey ]      ;; Upper vertical
road first junction
  ask patches with [ pxcor > 20 and pxcor < 25 and pycor < -4]  [ set pcolor grey ]      ;; Bottom vertical
road first junction
  ask patches with [ pxcor = 20 and pycor > 5]  [ set pcolor white ]               ;; White line Upper left
  ask patches with [ pxcor = 20 and pycor < -5] [ set pcolor white ]               ;; White line Bottom left
  ask patches with [ pxcor = 25 and pycor > 5]  [ set pcolor white ]               ;; White line Upper right
  ask patches with [ pxcor = 25 and pycor < -5] [ set pcolor white ]               ;; White line Bottom right
end
```