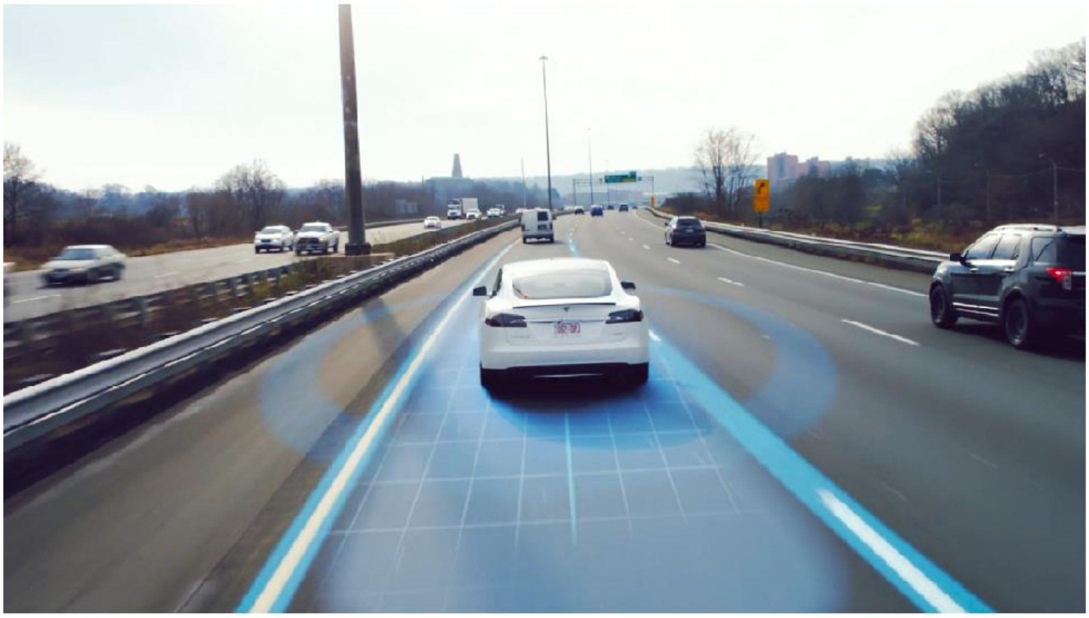
GIMA

Geographical Information Management and Applications

A study into the effects of assisted and autonomous vehicles on stop-and-go waves at on-ramps



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Abstract

Stop-and-go waves on highways are a product of human acting. As humans we are not perfect and other drivers are often hampered when changing lanes or braking. These disruptive actions can be prevented by introducing autonomous vehicles in the vehicle mix. In this research self-driving vehicles are represented by SAE-4 level vehicles. Autonomy levels of vehicles are made by the Society of Automotive Engineers (2014) and range from 0 to 5. SAE-0 are human-driven, while SAE-5 would correspond with a vehicle able to handle every situation. In this research human-driven, high-level automation (SAE-4) and low-level automation (SAE-2) are studied.

By creating a model which can simulate human drivers, low- and high-level automation on a highway, different vehicle mixes are explored. These vehicle groups are different in time headway and acceleration and are spawned on the main lane and an incoming on-ramp.
In the base scenario with 100% human-driven vehicles the on-ramp location is where the disruptive manoeuvres happen. Due to the high amount of vehicles on both lanes stop-and-wave forming actions are inevitable. These waves propagate with 7 km/h upstream and cause an average speed of 96.9 km/h which is 23 km/h lower than the maximum speed of 120 kmh. Besides the lower average speed is 1% of time spent in uncomfortable accelerations which decrease safety. The capacity of the base scenario is 3600 vehicles per hour.
If SAE-2 vehicles are added to the mix the capacity drops as does the average speed. In a scenario where 25% and 3% are equipped with SAE-2 and SAE-4 respectively which may happen in 2030, a capacity drop of 11.9% is observed. In addition the average speed also decreases with 10 km/h. At the same time the amount of uncomfortable deaccelerations decreases as well. In this scenario comfort and safety are increased while traffic flow is significantly worsened. This pattern is also visible in the 2035 and 100% SAE-2 scenarios, albeit that the effects are felt harder in these cases.

In contrast with the SAE-2 vehicles are SAE-4 equipped vehicles able to improve the traffic flow conditions. When 18% or more of the vehicles is equipped with self-driving capacities positive effects for traffic flow are felt. Capacity increases and less slowdowns are observed. If all vehicles would be autonomous, capacity would rise to 6000 vehicles per hour, congestion isn't present and all vehicles can drive the maximum set speed.

Acknowledgements

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At same the time kept Simeon Calvert me realistic. As an expert in traffic engineering, in which this thesis' subject tends, he knew what had to be done. Mainly he was a great help with the creation of the model used in the research. It was help that I really could use.

Special thanks to Job van Ginkel, Marijn Rieter, Nikki Keuper and Tobias Eckhart. The first three helped a lot with proofreading the concept version of this thesis. Due to this the quality was ensured. Tobias helped me with some code to accelerate the processing of the results in Excel. This saved me a lot of manual labour.

Laurens Kik,
Utrecht, April 12th, 2019

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List of Abbreviations

ACC:	Adaptative Cruise Control
ADAS:	Advanced Driver Assistance Systems
AV:	Autonomous vehicle
CACC:	Cooperative Adaptive Cruise Control
DLC:	Disruptive Lane Change
IDM:	Intelligent Driver Model
IDM+:	Intelligent Driver Model plus
LCA:	Lane Change Assistance
LiDAR:	Laser Imaging Detection and Ranging
SAE:	Society of Automotive Engineers
SAE-0:	Human-driven vehicle
SAE-2:	Vehicle equipped with SAE level 2
SAE-4:	Vehicle equipped with SAE level 4
TJP:	Traffic Jam Pilot

1. Introduction

Congestion has a lot of effects of which none can considered as positive. Millions if not billions of hours are wasted each day in stagnant traffic and humans are the ones to blame. Demonstrated is that stress and environmental pollution increase when congestion occurs (Marchesini & Weijermars, 2010) and that the loss of time and the corresponding decreased reliability on time is harmful for the economy (CEBR, 2014; KiM, 2017).
Paradoxically is economic growth also responsible for more congestion. According to VNO-NCW can 1% of economic growth directly be linked to 3% more traffic jams, at least in the Netherlands (Schravesande, 2017). Studies have shown that there can be only a fixed amount of cars per kilometre or the roads get too crowded and congestion occurs (Shefer, 1994; Shladover, Su & Lu, 2012; van den Berg & Verhoef, 2016). A small disruption in such traffic may cause a slowdown or even a traffic jam. Traffic jams and slowdowns are a product of human behaviour. A particular kind of jam is the 'phantom jam' or 'stop-and-go wave'. According to Hegyi and van de Weg (2013) 20-30% of traffic jams in the Netherlands can be classified as stop-and-go waves. These jams, which laymen often think occur with no apparent reason, hence the popular term 'phantom jam', are created by infrastructural bottlenecks and overcapacity. Research shows that tailgating or lane-changing activity and thus braking hard are a common cause of these stop-and-go waves (Laval & Daganzo, 2006; Ahn & Cassidy, 2007; Laval, 2007). In traffic with a high density and speed, small fluctuations of speed can disrupt the homogenous flow.

At one point on the highway these disruptions tend to pop more often: bottlenecks. At bottlenecks lane changes are needed. For instance, when a lane drops on a highway, drivers on that lane have to merge with the rest of traffic. Multiple studies have modelled how human drivers tend to change lanes (Ahmed, 1999; Choudhury, 2005; Ahammed, Hassan, & Sayed, 2008; Zhao et al., 2017). Observations and models of traffic have shown that changing lanes in dense traffic is the catalyst of stop-and-go waves. By hindering or even cutting off following driver's disturbances in traffic flow come up. Due to the high capacity of around 2400 vehicles per hour no space is present to react adequately on a hard-braking lead vehicle. The result is a chain reaction of braking and thus a traffic jam or jam cluster. This component of the stop-and-go wave is called formation (Laval, 2007). These clusters tend to move with a speed of 16 km/h in the opposite direction of the traffic. This movement is the second component of a stop-and-go wave named propagation (Laval & Leclercq, 2010).

A potential solution to prevent the occurrence of stop-and-go waves is the introduction of automated vehicles. If automated vehicles would become sophisticated and assertive they could react more adequately on situations on the highway than the human driver ever would be able to do. Of course, higher levels of autonomy are not present yet globally, but in the near future this should and could impact the way we drive on the highway. Therefore, it is of big importance to study the potential effect of these vehicles. This is done in a model which represents the real world. The choice was made to look at three groups of vehicles with different levels of autonomy. In this research a comparison between human-driven vehicles, Lane Change Assistance-equipped (LCA) and highly automated vehicles will be made. These groups correspond to SAE-levels 0, 2 and 4 respectively. The feasibility of these automated groups is high, albeit that the SAE-level 4 group is not driving on the road right now. It is expected that this will happen in the coming decade.
These levels refer to the standard created by the Society of Automotive Engineers (SAE). The SAE has created a ladder which divided AV's in ascending scale of autonomy. This was done to clarify the formerly blurred terminology used in the past. It consists of 6 levels ranging from level 0 to level 5. Level 0 has complete reliance on the driver while level 5 does have none (SAE, 2018).
LCA contains a blind spot warning, closing vehicle warning and the ability to execute the lane change. These features are mainly designed to increase safety and comfort. Most major car manufacturers' offer LCA on high-end models and their performance can said to be considerable

(Bartels, Meinecke & Steinmeyer, 2015). The few SAE-4 which high-level self-driving cars that are on the road now tend to have problems with merging and changing lanes when it is crowded. Online multiple videos are present which demonstrate the awkwardness of the driverless Waymo cars (Icer, 2018a; 2018b). Of course, this is the case for vehicles now and it is expected that a lot of improvements can be made to create a more AV. Questionable is if LCA-equipped and higher-level automated vehicles have a positive impact on traffic flow and capacity. Studies show that high penetration rates (>50%) are to be attained to profit from automated vehicles (Kesting, Treiber, Schönhof, Kranke & Helbing, 2007), but there is also evidence that vehicles with assistance will the decrease traffic flow (Calvert, Schakel & Lint, 2017).

1.1 Research objectives

To find out what the potential is of the lane-changing technology of SAE-Level 4 vehicles and vehicles equipped with LCA at highway bottlenecks a so-called microscopic simulation model is built. This simulation model is the central tool in retrieving results about the LCA-equipped and SAE-4 vehicles and their relation to 'normal cars'. These different levels of automation will have distinct ways of merging into traffic. By modelling characteristic behaviours related to these levels, different amounts of disturbances emerge which affect traffic flow.
The main objective is to learn if the possibility exists to reduce or even prevent stop-and-go waves on highways with tools as LCA or SAE-4. It is completely possible that LCA has a negative impact of the traffic flow due to the non-assertive programmed nature of the system. Therefore, suggested is to look at the possibilities that SAE-4 vehicles offer as well. In this way a comparison can made. Articles that compare vehicles with driver assistance and AV's are barely present. This thesis can fill that perceived gap.

Another important goal is to get insight about a maximum amount of cars on a kilometre of highway. Researched will be if it is possible to smoothen traffic flow at a bottleneck when a significant number of cars are equipped with LCA or SAE-4 automation when comparing with the contemporary situation. Besides is measuring the potential increase of lane capacity when introducing different percentages of LCA or SAE-4 vehicles to the mix an outcome worth looking at. These results can give insight in the potential highway situation of the (near) future. Depending on the penetration rates of these distinct levels of automation, the impact will differ.
By answering the upcoming questions, it will become clear what the impact of LCA and SAE-4 equipped vehicles can be on traffic jams, general traffic flow and capacity. This research is not aimed to study one situation so the outcomes are generic and can be applied to other areas and traffic situations.

The main objective of this research is to explore if certain traffic jams can be reduced or prevented by introducing various levels of autonomy in vehicles. This results in the following research question:

Research question: ***To what extent can vehicles equipped with SAE-level 2 or SAE-level 4 influence or prevent stop-and-go waves formed at bottlenecks?***
Sub questions:

1. What data and software are needed to create realistic simulations predicting the behaviour of and between LCA and SAE-4 equipped vehicles and human-driven vehicles?
2. To what extent does an LCA equipped vehicle differ with a SAE-4 vehicle and what various effects do both have on traffic flow when lane changing?
3. To what extent can the capacity of highway lanes be influenced by introducing LCA and SAE-4 vehicles?
4. Which types of traffic problems within the current traffic can be resolved by the introduction of LCA and/or SAE-4 equipped vehicles?
5. Are LCA equipped vehicles a solution to traffic problems in the Netherlands?

1.2 Research limitations

Due to restrictions in available time and data the scope of this research can be described as limited. The research question shows that the focus is on comparing LCA and SAE-4 equipped vehicles that merge in dense highway traffic. By including too many factors the research can be avoided to be broad. So, clear is that this research is looking at the role of automated vehicles and their impact on lateral movement. A sizeable amount of researchers (Ploeg, Serrarens & Heijenk, 2011; Shladover et al., 2012 & Fernandes & Nunes, 2012) have chosen to study the role of Adaptive Cruise Control (ACC), Cooperative Adaptive Cruise Control (CACC) and platooning of vehicles. Therefore, not a lot of scientific gaps were here to fill. Besides is longitudinal movement said to be less complex than lateral movement. Smaller steps are to be taken to understand this lateral nature.

The fact that the research is focussed and delimitated could make finding the right data a difficult task. Questioned can be if the right data is available right now. To surpass this limitation, the choice has been made to work with data which is possible to validate. Instead of modelling a real-life piece of highway, which requires specific data from that location, chosen is to model a more general situation. Here the goal is not to simulate every detail of a real-life situation but create a model more applicable for entrance lanes everywhere. In this way the parameters of the three different driver groups are central in the research. These parameters are extracted from the relevant literature.

2. Macro causes of congestion

In their article Rao and Rao (2012) see that there are micro and macro causes for congestion. In this chapter an overview is presented which indicates what macro factors lead to congestion. In many cases Dutch articles are used as these were widely available and serve as a great example when explaining macro causes of congestion. The micro causes are discussed in Chapter 3.

Due to a high population density and a high rate of car ownership heavy traffic and congestion at bottlenecks in the Netherlands is inevitable. According to Bovy (2001) did the use of cars more than double between 1976 and 2001. Other causes of this growth than an increase of inhabitants and car ownership are increased quality of the roads and income growth in the Netherlands. Figure 2.1 shows in which way these factors influence each other. This figure makes clear that the equation leading to congestion can be described as complex. While it seems an option to enhance the highway system by building more roads, this can indirectly lead to more car use and more long-distance trips. As roads improve, more people drive, until each road segment is just as busy as before (Duranton & Turner, 2011).

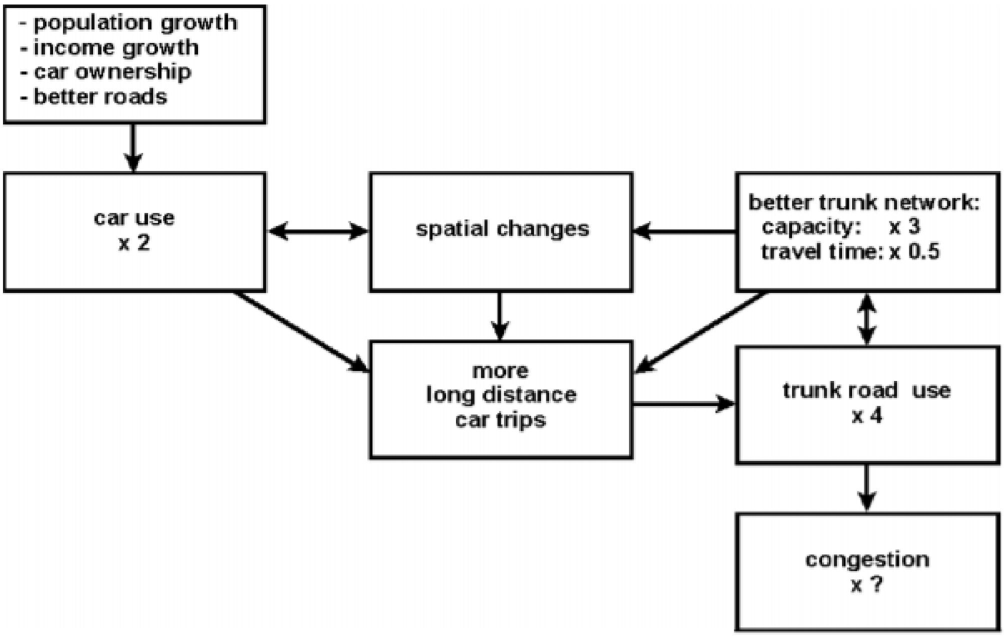

Figure 2.1: Main factors contributing to congestion from 1976-2001 (Bovy, 2001)

Arnott and Small (1994) proved mathematically that building new roads in many cases isn't a solution for congestion problems. This is due to the Pigou–Knight–Downs paradox. Stated can be, if the paradox applies, is that expanding a highway system is often ineffective or counterproductive when the intention is to prevent congestion (Downs, 1992). The paradox is based on the Lewis–Mogridge position which explains that as more roads are built, more traffic consequently fills these roads. Within months or weeks speed gains on the network are lost. In a few cases new roads can help reduce congestion, but the most probable outcome of a new road is a shift of congestion to another road segment (Mogridge, 1990). More recent research has confirmed the attraction of more highway lanes. The amount of available kilometres of lane can be directly linked to the number of vehicle-kilometres travelled (VKT). One of the conclusions states that "*building new roads and widening existing ones only results in additional traffic that continues to rise until congestion returns to the previous level*" (Duranton & Turner, 2011). Thus, increasing macro capacity by constructing new and broadening existing roads is often not a viable option, despite this is often done due to political choices.

2.1 Developments affecting traffic

The developments in mobility are determined by developments in roughly four areas: economy, spatial planning, demography and sociocultural factors (SWOV, 2013).

2.1.1 Economic factors

The Dutch motorways are among the most intensively used roads in the world. Due to the growing economy, the number of vehicles and thus traffic jams on the national roads is increasing (KiM, 2017). It is proven that during times of economic prosperity the amount of vehicles on the road grows, which can result in more and longer traffic jams. VNO-NCW showed that in the Netherlands 1% of economic growth can directly be linked to 3% more traffic jams (Schravesande, 2017). Statistics from all over the globe confirm that economic prosperity is correlated with car ownership. Extreme examples that confirm this are India and especially China. Between 1980 and 2005 the income per capita of India more than doubled, while the Chinese figure more than quadrupled. This income growth had direct consequences for car ownership in the country, which is an indication for car use. Since 1990, the total number of motor vehicles has tripled in India and has increased tenfold in China (Pucher et al., 2007). Figure 2.2 shows the ownerships of motor vehicles for 2000 and a projected graph for 2050 (Chamon, Mauro & Okawa, 2008).

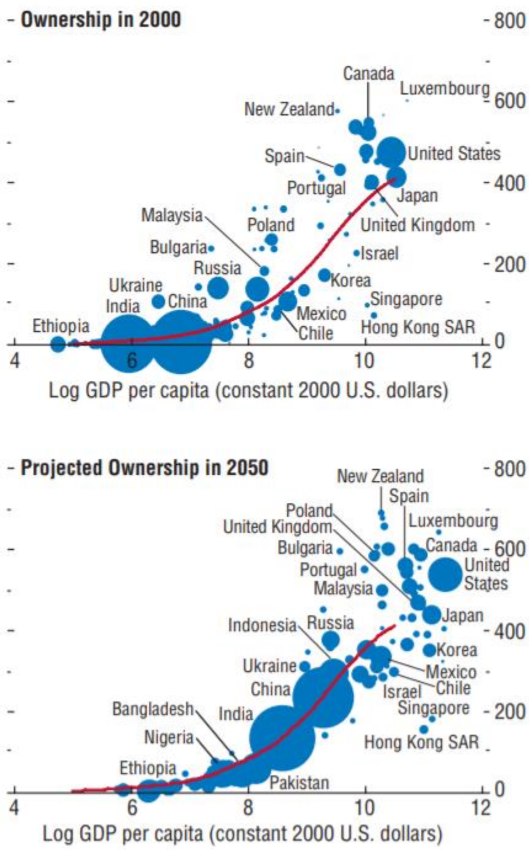

Figure 2.1: Car ownership per GDP in 2000 and 2050 (Chamon, Mauro & Okawa, 2008).

In the Netherlands extreme growth rates like the ones in India and China will not be present nowadays. Still is the impact of economy tangible on car use and congestion. Three factors tend to be responsible for a loss in travel time. The most important explanatory factor behind the increase in travel time loss is GDP. The GDP is expected to grow by 11 percent between 2017 and 2023. This GDP growth results in a greater car ownership rate.

The second mentioned factor in the study by KiM (2017) is the oil price. The average fuel price in 2023 is projected to be about 3 percent lower than the level of 2017. A consequence is more travelled vehicle kilometres which lead to a small increase in travel time loss. The extra road capacity by 4 percent limits the increase in congestion up to and including 2023. The estimation is that between 2018 and 2023 the amount of traffic on the highways will grow with 10.7% (KiM, 2017). All these factors together give an indication that smart solutions are in place if congestion is to be confined.

2.1.2 Spatial planning

Besides the economy are other factors of importance when looking at increasing car use and kilometres ridden. The RIVM, the Ministry of Health, Welfare and Sport (2006), acknowledges that the urban environment in the Netherlands stimulates taking the car. Inhabitants of relatively new neighbourhoods built after 1971 at the edge of the city tend to use the car more during peak hours than inhabitants which live in the city contours before 1971.

Another flaw in urban planning is the location of employment. The amount of businesses around the highway has grown, while locations near central train stations have not. The consequence is that more employees are destined to take the car instead of public transport. This has a negative impact on the crowdedness of the Dutch highway system (RIVM, 2006).

The Netherlands is still urbanizing, which has resulted in compaction of in the urban area, but also the spread of the city to the countryside. This process will evidently continue for another decade. A direct consequence of the spread to the countryside is the diffusion of traffic on a greater area, which results in longer distances driven when commuting. As a result, the dependence on the car increases and the utilization of public transport and the bicycle drops (SWOV, 2005).

2.1.3 Demography

The Netherlands is the fourth most population-dense country with more than 10 million inhabitants (World Bank, 2017). This is the main reason why the Dutch highway system can be said to be among the most intensively used in the world. At the moment the population is 17.3 million. This figure is still growing with an average of 0.54 percent per year (CBS, 2018). Van Dam, de Groot and Verwest (2006) show that an increase in inhabitants results in an increase of kilometres ridden. The mobility development partly depends on demographic developments; so is the increase of the mobility in terms of the number of kilometres driven per car partly caused by population growth.

Striking is that the increase in mobility is for a larger part caused by an increase in mobility per person: mobility mainly increases because of people are more on the road, not so much because there are more people commuting (KiM, 2017).

2.1.4 Sociocultural factors

The last group of factors is a product of society. It can be questioned which cultural and gender groups' use the car to move around. SWOV (2013) observed that two sociocultural processes have the greatest impact on the amount of hours spent in vehicles. The first process is the growing individualization in the Dutch society. People tend to use cars more alone and more privately and the amount of cars is growing as well (KiM, 2017). The other impactful sociocultural process is the ongoing emancipation of women. This positively affects their participation in the job market and thus the use of cars. This increase in mobility has direct consequences for the number of vehicles on the roads (SWOV, 2013).

2.2 Economic impact of congestion

The previous segment showed that the economy has impact on the amount of vehicle kilometres ridden by car. Vice versa impacts congestion the economy. Employees and goods are standing still in traffic, which negatively affects the amount of hours worked and increases the time to transport products respectively. CEBR (2014) has studied and forecasted the cost of traffic jams in Europe and the US. Estimated is that the cost of congestion in these regions combined may reach $293.1 billion by 2030. This is almost a 50% increase from 2013.
In the Netherlands this figure is growing as well. The societal cost of congestion was calculated to be between the $3.2 and $4.2 billion in 2016, an 11% increase compared to 2015. This loss is for 70% accounted to the increasing amount of hours lost in vehicles. The remainder 30% is due to the deterioration in the reliability of travel times (KiM, 2017).

3. Traffic flow and congestion

To gain insight in the workings of congestion it is essential to obtain some prior knowledge on traffic flow. Real-life experiments have shown that three different kinds of traffic are apparent on highways: free traffic flow, where vehicles have the space to merge lanes and to pass others, synchronized traffic flow, where vehicles do not have the space to pass freely due to a high density, and lastly traffic jams. The complexity of traffic flow is to evince the transitions between these states (Kerner & Rehborn, 1996). An example of a trigger of a space-time transition is the disturbances in synchronized flow in which a stop-and-go wave can form.

In free flow all vehicles are able to drive at their desired speed. In models this speed is called 'vmax'. In this state of free flow, the maximum capacity of the highway is not reached (Knospe, Santen, Schadschneider & Schreckenberg, 2000). This enables the drivers to surpass others and switch lanes at their own will. It demands an increase of vehicles before the transition towards the next stage is made. If the highway gets more crowded synchronized flow occurs.
Synchronized flow is characterized by a near maximum capacity. This synchronized flow mainly occurs in the vicinity of on- and off ramps, the place where congestion often occurs as well (Kerner & Rehborn, 1997). This metastable stage can result in the forming of stop-and-go waves which are often wrongly referred to as phantom waves. Due to small disruptions in the synchronized flow a new less homogenous flow arises in the form of stop-and-go waves (Helbing, 2001). Further explanation of this process is extended on in chapter 3.3. Congestion cannot occur directly from free flow but must go through the synchronized flow state before it can happen. For recoveries the same principle applies. A traffic jam will always flow in to synchronized flow before the free flow state is achieved (Brilon, Geistefeldt & Regler, 2005).
Before the workings of the three flows and traffic wave forming can be explained a look must be given at congestion.

3.1 What is congestion?

In their article, Rao and Rao (2012) divide the causes of congestion in two classes. According their research are macro and otherwise micro-level factors influential if and where congestion occurs. The previous chapter showed the macro-level factors which are of influence in the Netherlands. In this segment the micro-level factors will be discussed.

Maibach et al. (2008) state that "*congestion arises from the mutual disturbance of users competing for limited transport system capacity*". This broad statement is not a measurable definition yet. The Ministry of Infrastructure and Water Management defines congestion and divides it in three distinct groups (Rijkswaterstaat, 2018a):

1. **Slow-moving traffic:** traffic that does not drive faster than 50 kilometres per hour, but often goes faster than 25 kilometres per hour; should persist two kilometres or longer.
2. **Stagnant traffic:** traffic that drives less than 25 kilometres per hour for two kilometres or more.
3. **Slow to stationary traffic:** slow-moving traffic over longer distances with stagnant elements on some traffic.

The division of congestion by Rijkswaterstaat (2018a) eases the measuring of the length and severity of traffic jams but does not capture the essence of congestion. Bando, Hasebe, Nakayama, Shibata and Sugiyama (1995) reason that "*congestion exists which is induced by a small perturbation without any specific origin such as a traffic accident or a traffic signal. This kind of congestion is often observed in a highway or freeway. We can regard this congestion phenomenon as the instability and the phase transition of a dynamical system*." In essence congestion is a state of traffic in which disruptions have forced traffic to slow down or even stop. The origin of these disturbances differs. These are described in the next segment.

3.2 Types of congestion

In an article by Hegyi and van der Weg (2013) a division of congestion causes is given. Roughly can said be that there are three types of traffic jams with distinct characteristics: bottleneck congestion, congestion formed due to incidents and stop-and-go waves.

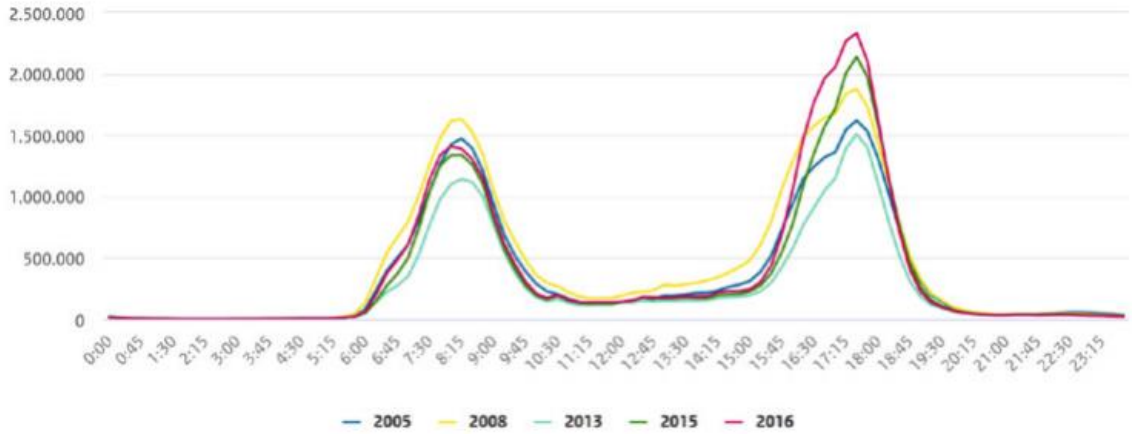

Figure 3.1: Amount of hours lost in traffic during workdays in the Netherlands (2005-2016) (KiM, 2017)

Congestion at bottlenecks is often a reoccurring phenomenon. It takes place at road segments where lanes are dropped, or extra traffic comes in. Observed is that bottleneck congestion rises at the same time at different days (Li et al., 2015). During morning and evening rush hours the highway simply does not have enough capacity to cope with the inflowing traffic. Figure 3.1 is an example that shows the hours lost in the peak moments during workdays (KiM, 2017).

Congestion formed due to an incident has a more temporal character. A car collision, bad weather or roadworks can be factors for forming traffic jams. Due to the unpredictability of these cases often congestion occurs at road segments which do not overcrowd daily.

Research by Treiber, Hennecke and Helbing (2000) show that the cause of traffic jams barely affects the form of congestion. In their study traffic jams on German and Dutch highways were observed and analysed. Concluded was that the majority of traffic breakdowns are triggered by stationary inhomogeneity. These include classic bottlenecks like on- and off ramps, gradients and lane narrowings or –closings. Another, quite striking, finding was that incidents in the opposite lanes are part of this group of bottlenecks as well. Accidents on the highway can affect both directions' traffic flow by obstructing lanes in one way and triggering 'rubbernecking' in the other direction (Masinick & Teng, 2004).

3.3 Stop-and-go waves

Stop-and-go waves are not only a recent studied phenomenon. A study done by Chandler, Herman, Montroll (1958) already showed that a certain homogeneous density range of traffic flow cannot exist due to instability which can result in phase transitions (Krug, 1991) or spontaneous symmetry breaking (Evans, Foster, Godrèche & Mukamel, 1995). These two highly physics related phenomena are the initiators of the occurrence of stop-and-go waves. Progression aimed to extend the understanding on stop-and-go waves was mainly made in the 1990's and early 2000's. With the help of the studies by Krug (1991) and later Evans et al. (1995) on the psychics behind wave forming, researchers like Kerner and Konhäuser (1993) Kerner and Rehborn (1996 & 1997), Lee, Lee & Kim (1998) and Treiber, Hennecke and Helbing (2000) and many more could explain how traffic states and congestion cohere.
These studies show that the process of clustering of traffic can directly be linked towards the disruptions, or more exact: perturbations, which happen in moving synchronized traffic. The presence of synchronized traffic is proven to be a prerequisite for the formation of stop-and-go waves. Formation is the first of the two components of stop-and-go waves is built of. The second is propagation which is described further on.

Del Castillo (1996) shows in his article that not all disturbances result in traffic jams. This is backed up by the study by Helbing (2001). Here is acknowledged that *"Even under comparable conditions, some perturbations grow and others fade away"*.

Further research shows that tailgating or lane-changing activity and thus braking hard are the common cause of the stop-and-go wave creating perturbations (Laval & Daganzo, 2006; Ahn & Cassidy, 2007; Laval, 2007). In traffic with a high density and speed small fluctuations of speed can disrupt the homogenous flow. In real-life experiments Sugiyama et al. (2008) show that these tiny disruptions are sufficient to create jam clusters. In practice these conditions of the experiments of high density and speed are often not present. In many cases, stop-and-go waves are a product of an infrastructural situation. Road segments containing bottlenecks are often the location where stop-and-go waves form. In the Netherlands 20-30% of traffic jams can be classified as stop-and-go waves (Hegyi & van de Weg, 2013).
Stop-and-go waves are often wrongly referred to as 'phantom jams', which would suggest that they are formed without a reason which is proven to be untrue. Still this term is sporadically used in consulted literature (Helbing, 2001).

The propagation of a stop-and-go wave contains the upstream movement of the cluster. This movement is created due to the constant stopping and accelerating of vehicles. The reason for existence of the stop-and-go wave is the greater deceleration of vehicles during the braking than the increase of acceleration when escaping the wave in the front. Due to this variance a movement upstream is created. Laval and Leclercq (2010) show that the speed of this movement is 16 km/h. Figure 3.2 visualizes this upstream movement and speed.

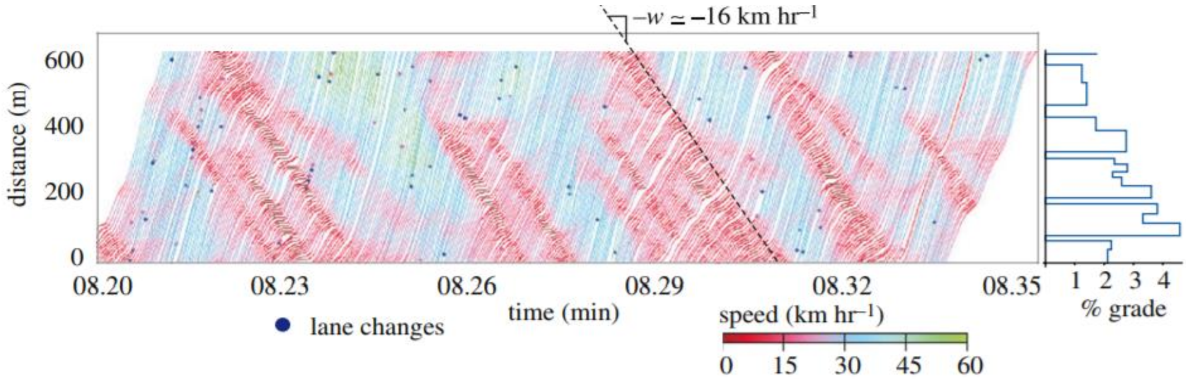

Figure 3.2: The formation and propagation of stop-and-go waves for the median lane in the vicinity of Lankershim Avenue on US-101 freeway in Los Angeles, CA (Laval & Leclercq, 2010)

3.4 Capacity

The capacity of a highway can be defined as "*the maximum flow rate that can reasonably be expected to traverse a facility under prevailing roadway, traffic, and control conditions*" (HCM, 2000). Another explanation of the term is that capacity is a maximum threshold. Below this maximum traffic flow performance is acceptable, above proper operation fails (Brilon, et al., 2005). This capacity is often expressed in vehicles per hour. A capacity value only applies to a specific situation and for specific circumstances. In the Dutch manual for capacity values for highways these circumstances are clearly demarcated (Goemans, Daamen & Heikoop, 2011):

- Design in accordance with the current guidelines for motorways;
- No large objects (very) close to the road, for example noise barriers;
- No steep slopes (> 2%) or gentle slopes over long distances;
- In daylight and in dry weather (less than 2 mm precipitation);
- A good state of the road surface;
- With traffic signalling, but without traffic management measures;
- A default percentage of freight traffic of 15%.

Under these standard circumstances certain capacity values per lane are observed. These are composed by making use of literature, observation and modelling. Table 3.1 shows these values. Striking is the uneven increase of the capacity per road segment. Evident is that drivers take more space when a highway segment consists of four lanes or more. It is more efficient to construct a highway which consists of two sets of two lanes than a segment with four lanes.

Table 3.1: Capacity values at 15% freight transport (Goemans, Daamen & Heikoop, 2011)

Road section	Capacity (vehicle/hour)	Increase compared with previous situation
1 lane (length > 1500 m)	1.900	N. A
1 lane (length < 1500 m)	2.100	200
2 lanes	4.200	2.100
3 lanes	6.300	2.100
4 lanes	8.200	1.900
5 lanes	10.000	1.800
6 lanes	11.500	1.500
7 lanes	13.000	1.500

The clear demarcated list of circumstances indicates that capacity is not static but fluent. Under certain circumstances a deviation of these capacity values occurs. Infrastructural, weather and traffic management factors and amounts of freight traffic all affect the capacity. Most circumstances decrease the capacity of a segment. Only a decrease and a ban of overtaking by freight trucks and the dosing of merging traffic from on-ramps are observed to have positive impact on the standard capacity, the rest of the factors can all be considered as negative.
Goemans et al. (2011) also show the impact of merging vehicles on capacity. Vehicles that overtake need more space than ones which stay in lane. Higher percentages of vehicles which have to merge to enter the highway result in lower capacities. The impact of merging vehicles on traffic flow and capacity is further extended on in 5.1.

3.4.1 Capacity drop

A term related to capacity is the 'capacity drop'. At a capacity drop the maximum traffic flow through coming in a bottleneck is higher than the outflow of congestion. Due to unclear reasons the outflow capacity of stop-and-go waves tends to be lower than that of 'regular' traffic jam (Yuan, Knoop, Leclercq & Hoogendoorn, 2017). Research shows that a 6% drop is observed after some forms of congestion (Ponzlet, 1996). A higher average percentage of 24% is found when comparing the stochastic capacity to flow rates in congested flow (Brilon & Zurlinden, 2003).

4. Automation levels of vehicles

This chapter explores the different levels of automated vehicles. Which definitions are used in literature and how can these terms be used in this research? This information can be used in the next chapter on the parameters which make up the different behaviours of the human-driven, LCA-equipped and SAE-4 groups on the highway.

4.1 The SAE-ladder

To be clear about which level of automation is talked about a division is needed. There are still articles written about self-driving cars in which it is unclear what level of automation is spoken (Roy, 2018). Shladover (2016) acknowledges that 'the media' have blurred the terminology around automated driverless systems. To clarify the terminology, the SAE (2014) created and updated (SAE, 2018) a ladder that divides the systems in an increasing order. Level 0 has complete reliance on the driver while Level 5 does have none. Figure 4.1 is an overview of the SAE ladder.

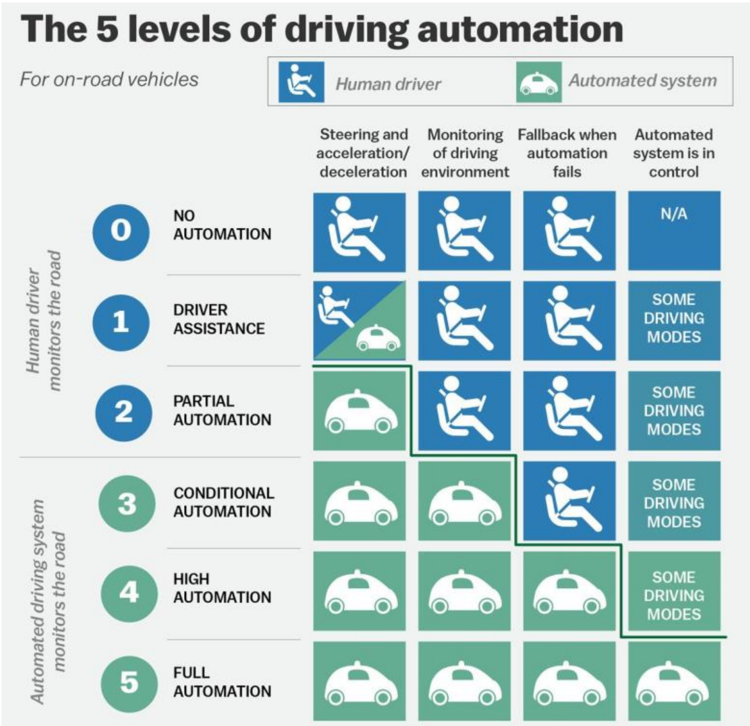

Figure 4.1: Automation levels of autonomous vehicles (SAE, 2018)
Image Courtesy: Vox (2016)

4.1.0 SAE Level 0

This first level actually contains no automated functions, hence the term Level 0. In Level 0, the driver has to sit behind the steering wheel with his legs on the clutch plates and the brakes. So, this level refers to conventional vehicles (Chaturvedi, 2018).

4.1.1 SAE Level 1

Here the driver is still responsible for driving the vehicle but is assisted to a certain extent by the vehicle. A vehicle classified as level 1 can assist in one driving task, but more assistance tasks are possible. Examples of this are automatic braking or lane-keeping assistance (Chaturvedi, 2018). These functions are part of the comprehensive ADAS-group. ADAS stands for Advanced Driver Assistance Systems and contains dozens of functions of which many are not supporting driving tasks. Each sensor with an own functionality, like rain and parking sensors, can already be described as an ADAS function. Clear is that within ADAS a gradation of complexity and usability is present. Lane Change Assistance for instance can be considered as more complex functionality which provides a form of automation. If a vehicle is equipped with one of these functionalities which assist a driving task, it can be classified as a SAE-1 automation. Less complex systems which are also part of this ADAS-group like rain sensors and navigation are not part of this group (Lu, Wevers, & Van Der Heijden, 2005).

4.1.2 SAE Level 2

Level 2 vehicles take over more responsibility when compared to Level 1. The vehicle can assist with steering and acceleration. Still, the driver must be aware to react on what is happening on the road. Examples of level 2 automated vehicles contain Tesla's Autopilot and the combination of more general assistance groups like Adaptive Cruise Control (ACC) and Lane Change Assistance (LCA) (Chaturvedi, 2018).

In this research the focus is on lateral movement. One goal is to show what the impact of merging low and high-level automated vehicles is on traffic flow. In practice newly sold vehicles tend to have multiple automated functions under the hood, but the question is if these functions can be used simultaneously. If a vehicle can assist both lateral and longitudinal movements at the same time, the vehicle can be allocated to the SAE-2 group.

An automated function which impacts merging is LCA. Lu et al. (2005) define LCA as a function which is designed for change-of-lane manoeuvres, will provide information about vehicles in adjacent lanes and warn for potential collision. It can have the option to take vehicle control in case of imminent collision. It is mainly designed with a safety enhancing functionality in mind. How this will affect traffic flow is the question. Does making use of LCA vehicles take more space than a human driver would and thus impact traffic flow negatively? A study by Calvert, Schakel and Lint (2017) has been set up to determine the impact of lower levels (SAE-1 & 2) of automation. Reasoned is that in the near future there will be a transition towards partial vehicle automation instead of high-level automated vehicles. It is questionable if this transition will be positive for traffic flow and highway capacity. This reasoning contradicts the many studies which deliver evidence concerning positive impact of automated functions on these two essential elements for highway traffic. This positive effect of automated cars would mainly arise on sufficient penetration (Kesting, et al., 2007; Shladover, et al., 2012). It is unclear in what way LCA-equipped vehicles will influence traffic flow stability. As this function is designed for comfort and safety the question is how these vehicles will interact with completely human-driven and higher level of automated vehicles. Besides, it remains uncertain to what extent humans are going to use LCA. These unknown factors make estimating the exact impact of SAE-1 and SAE-2 level automated vehicles difficult (Calvert et al., 2017).

4.1.3 SAE Level 3

At Level 3, the majority of responsibilities of safety-related functions are in hands of the vehicle. By making use of LiDAR (Laser Imaging Detection and Ranging), advanced sensors and algorithms the vehicle can perform "dynamic driving tasks" but need human intervention in some situations. Audi has scheduled to launch a level 3 automated sedan in 2019. This Audi A8 comes with Traffic Jam Pilot (TJP) which is a mode that can manage traffic at speeds up to 60 km/h hands-off in select situations (Paukert, 2018).
Carsten, Lai, Barnard, Jamson & Merat (2012) show that drivers' visual attention to the road centre decreases as the level of automation increases. Stated is that "*when tracking and regulating in driving are automated, the driver will be faced with little need for input and attention*". A direct consequence of this is the increase of reliance in the automated vehicle when the level of capability rises, resulting in higher amount of engagement in non-driving-related tasks, like watching DVD's or reading. This is especially true for drivers when given lateral support as compared to when given longitudinal support. The correlation between higher automated vehicles and non-driving-related tasks and thus distraction can be potentially dangerous. Drivers making use of Level 3 automated vehicles may be "*lulled into a false sense of security*" due to the unawareness of the

flaws of these vehicles. There are still situations where the human driver has to intervene. When distracted, drivers can be slow to react, which can result in an increase of collisions (Solon, 2018).

4.1.4 SAE Level 4

The fourth level compasses automated steering, braking, accelerating, decelerating, monitoring the vehicle and external environment as well as responding to events in real-time and determining when to change lanes, turn, and use signals (Chaturvedi, 2018). Level 4 vehicles have control which should ensure for safety by executing all safety-critical driving functions. This level is designed to monitor roadway conditions for an entire trip (Reese, 2016). The Waymo cars are an example of this Level 4 automated vehicle. The difference with SAE Level-5 is that not all driving modes are supported. A Level 5 vehicle would be the 'perfect machine' that would recognize every situation and can react adequately to this. Level 4 is not able to do this yet and can be considered as the most feasible autonomous vehicle for now (Litman, 2017).

4.1.5 SAE Level 5

Level 5 is the final stage of the SAE ladder (SAE, 2018). The vehicle is in full control and is capable of taking adequate decisions in every situation. No human intervention is needed and due to this the need for a steering wheel and pedals disappeared. Even drivers are not necessary. The feasibility of this level is low, due to the relative amount of distinct interactions that autonomous vehicles have to be able to handle. When comparing the amount of lines of code of aircraft, which come across a low amount of different situations, with modern luxury vehicles a great contrast is visible. Figure 4.2 shows this. Autonomous vehicles will encounter a myriad of situations. Imagine different amounts and directions of traffic consisting of cyclists, pedestrians, buses and cars. It is an enormous challenge to program vehicles to perform well in all these situations (Litman, 2017).

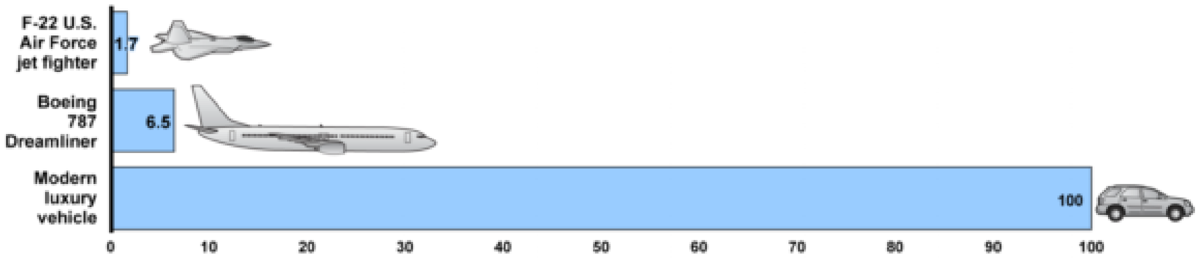

Figure 4.2: Average amount of million lines of codes in a modern luxury vehicle comparing to aircraft (Litman, 2017)

4.2 Development of automation in the near future

Experts expect that some levels of automation won't influence traffic flow positively. There is a probable chance that the developments towards full-automated vehicles will have a negative effect, especially in period about 5-20 years from now. In this time frame the amount of ACC and LCA equipped vehicles will grow considerably. Figure 4.3 shows expected rates of certain automated vehicle groups in the coming years. It is sensible to keep in mind that according to Calvert et al. (2017): "*the figure is by no means meant to be definitive but is meant to give an indication of the duration of the transition phase and what percentages of different automated technologies may be present simultaneously, which is relevant for simulating different types of vehicles.*" This last point makes this figure fit greatly in this thesis.

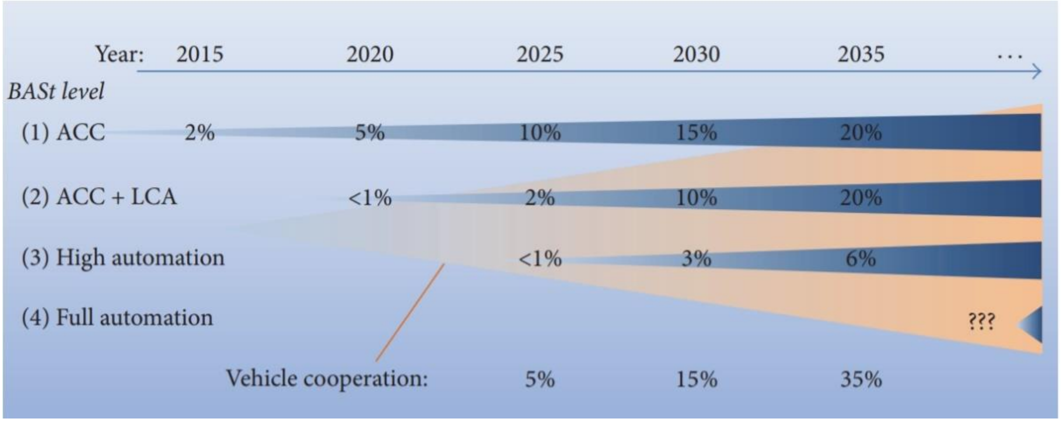

Figure 4.3: Estimated automated vehicle share on roads (Calvert et al., 2017)

The expectation exists that the growth of automated vehicles won't be as spectacular as some popular media suggest. High-level automated vehicles will have considerable impact, but as mid-tier automated vehicles are designed for safety and comfort, which will result in longer time headways, traffic flow will not enhance. On the contrary, it is expected that capacity on highways will drop in this period. Only at high penetration rates will automated vehicles impact congestion positively.

Thereby it is important to point out that the durability of personal vehicles result in relative long replacement time. The replacement time of a complete vehicle fleet in a country takes approximately 15 years (Tillema, Gelauff, Waard, Berveling & Moorman, 2017). The consequence is that it will take decades before high penetration rates of automation, thus the benefits, are achieved (Litman, 2017). Until then the interaction between human and automated vehicle will likely bring problems. Unexpected behaviours and inattention of drivers are examples of uncertainties in predicting the effect of automation in this period (Bültmann & Houben, 2016).

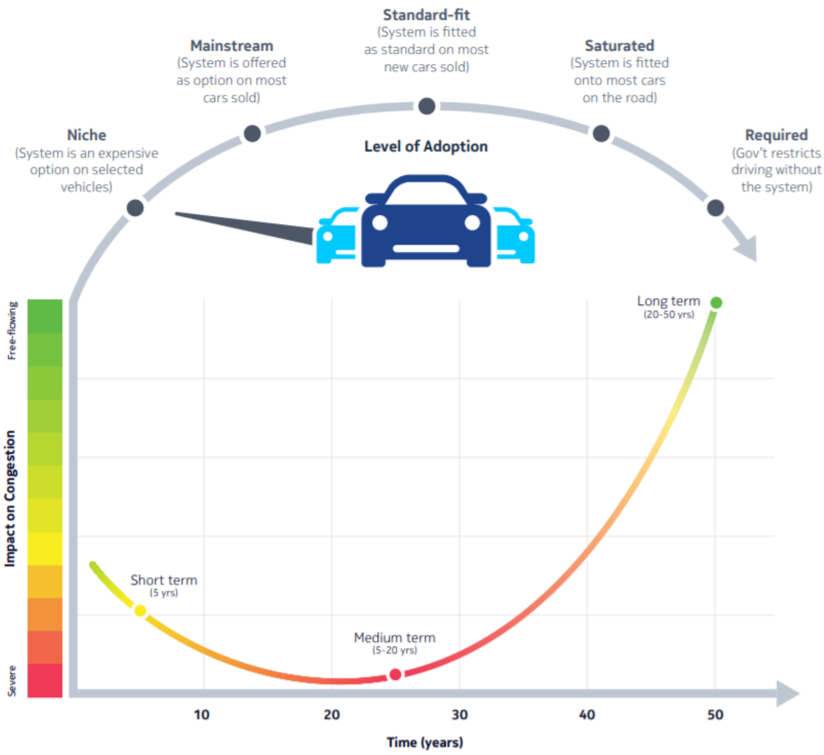

Figure 4.4: Estimated impact of automated vehicles on congestion (Bültmann & Houben, 2016)

4.3 Effect of automated vehicles on capacity and traffic flow

Previously done studies have shown that introducing automated vehicles would have a positive impact on traffic flow. Models designed to observe the impact of ACC and CACC predict a promising future with increases of capacity up to 414% (Fernandes & Nunes, 2012). However, these exciting percentages only occur at high penetration rates and are heavily dependent on the traffic-flow conditions. The effect of CACC is mainly observable in conditions with high-traffic volume combined with a high percentage of CACC-equipped vehicles in the vehicle fleet. The result is a more interactions in a CACC-platoon and thus reduced time gaps (van Arem, van Driel & Visser, 2006).
For non-cooperative, low level automation, SAE-1 and 2, this high penetration rate also is necessary to have a positive impact. Just like cooperative automation a high rate is needed to achieve any gains in traffic flow. More than the half (50%) of vehicles would have to be equipped with automated features to reach this (Kesting et al., 2007). It is still unclear if low penetrations of low and high automation will affect traffic flow or may even harm it. Some state that these low levels of penetration do not bring any negative effects to traffic flow, but Calvert, Soekroella, Wilmink and van Arem (2016) remark that "*there is a growing consensus that traffic flow will be negatively affected*". These negative effects are observed in multiple studies focussed on the relationship between automated driving and traffic flow (van Arem et al., 2006; Kesting et al., 2007; Hoedemaeker & Brookhuis, 1998; Marsden, McDonald & Brackstone, 2001).

Full penetration of autonomous vehicles should have a positive impact, but in which gradation is unclear. Van den Berg & Verhoef (2016) show that the results of comparable studies tend to strongly differ. Besides is there a significant difference on capacity between uncooperative and cooperative autonomous vehicles. Table 4.1 shows the differences between the ACC and CACC studies. This difference indicates that vehicle connectivity and cooperation are key in improving traffic flow and safety on the highway (Timmer, Kool, Pel, van Est & Brom, 2015; Shladover, 2009).

Table 4.1 Increase in capacity from switching from only normal cars to only autonomous cars (van den Berg & Verhoef, 2016).

Study	Uncooperative autonomous cars	Cooperative autonomous cars
Chang and Lai (1997)	33%	X
Fernandes and Nunes (2012)	X	84–230% at 36 km/h, 186–414% at 72 km/h
Ni et al. (2010)	X	20–50%
Shladover (2011)	X	80%
Vander Werf et al. (2002)	7%	Around 220%
Shladover et al. (2012)	1–4%	97%
Tientrakool et al. (2011)	90% at 50 km/h, 40% at 100 km/h	200% at 50 km/h, 270% at 100 km/h

In what way automated vehicles cause disruptions which can trigger stop-and-go waves is hard to say. Theoretically high-level vehicles should merge seamlessly into traffic. As these AV's are designed to drive safely, while reducing distances to increase traffic flow no perturbations should occur. This applies to CACC-equipped vehicles and not per se for ACC-equipped vehicles in which short braking actions introduced by a platooning vehicle still will be amplified in upstream direction (Ploeg et al., 2011). SAE-2 level vehicles equipped with LCA and ACC are thus still susceptible to stop-and-go wave forming.

The essence of stable traffic flow is that disturbances upstream are not felt more heavily downstream. If high level automated vehicles are added to the mix the needed space between leading and following vehicles can decrease. Here the capacity gain is won. In a perfect situation all vehicles are automated and connected. In this situation the string stability is higher than now. Cars can follow more closely, but this has not to be positive for traffic flow stability, which is a different term. Darbha and Rajagopal (1999) make a clear distinction between string stability and traffic flow stability. String stability is "*stability with respect to intravehicular spacing; intuitively, it ensures the knowledge of the position and velocity of every vehicle in the traffic, within reasonable bounds of error, from the knowledge of the position and velocity of a vehicle in the traffic. String stability is analysed without adding vehicles to or removing vehicles from the traffic*". Traffic flow stability focusses on the development of velocity and density related to the addition and/or removal of vehicles from the flow. Stable string stability does not ensure a stable and desirable traffic flow. More factors than only intravehicular spacing are affecting traffic flow. If the coupled set of equations on velocity and density is stable, the traffic flow is stable as well. In summary; changing the average necessary space between leading and following vehicles is not the only factor impacting traffic flow and its stability (Darbha & Rajagopal, 1999).

If string stability is secured, perturbations in traffic should fade away instead of amplify. Due to the human reaction time of around one second, adequate response in shorter space headways than that one second seems impossible. In theory AV's should diminish the space headway to the absence of this reaction time. Noted should be that computational time is a relevant element as well. It seems that AV's demand around ten times less space headway. In practice are the differences between a human driven and an automated vehicle smaller than demonstrated in literature. Observations have shown that some drivers drive as close to their leading vehicle as 0.3 seconds. These drivers do not only keep an eye on the immediate vehicle in front, but the vehicles further ahead as well. This allows for reacting on these vehicles, which decreases the space headway needed to avoid accidents. If this smaller headway impacts the occurrence of perturbations is not clear (Treiber, Kesting & Helbing, 2006a).

5. Effect of merging traffic

As the focus of this research is on stop-and-go waves formed at a bottleneck insight has to be created how humans would merge. What methods are used to explain merging behaviour and do LCA-equipped and self-driving change lanes similar to human-driven vehicles? Interesting is to see if these lane changes are also wave forming.

As shown earlier, Ahn & Cassidy (2007) found that a sizeable number of shockwaves at the investigated highway were initiated by lane changes. If no lane changes were needed no perturbations and thus no stop-and-go waves would occur. But reality is that on- and off-ramps and non-American overtaking rules on the highway incentivize lane changing. A lane change which hampers a following drivers' constant velocity can result in the formation of a stop-and-go wave. To investigate which lane changes are responsible for wave forming perturbations a look must be given to merging. In literature a division between three distinct merging actions exists. These types are dependent on the circumstantial conditions which trigger lane-changes. Park & Smith (2012) describe the three types as follows:

- Discretionary lane-change: A lane-change aimed at improving his/her driving conditions.
- Mandatory lane-change: A forced lane-change because of unavoidable conditions, such as the end of a merging lane.
- Courtesy lane-change: A type of lane-change where place is made for other vehicles. A simple slowdown to yield for other vehicles also can be accounted to this group.

In general, it can be said that mandatory lane-changes generate more conflict than discretionary or courtesy lane-changes. This is due to the more aggressive behaviour during mandatory lane changing situations compared to discretionary and courtesy lane changing situations (Ahmed, 1999). By reducing the amount of mandatory lane-changes less aggressive, safer and for this research important, more stable interactions will occur.

To a certain extent humans are able to avoid risky wave forming lane-changes, but we aren't perfect drivers. For this reason, introducing AV's and LCA-equipped vehicles should result in fewer disturbances due to merging.

5.1 Stages of lane changing

In previous research changing lanes is often modelled in two or three stages (Ahmed, 1999; Choudhury, 2005). According to Ahmed (1999) a driver decides to consider a lane change first, which is directly followed with a choice for a target lane. The last stage is the acceptance of a gap in the target lane. In the article of Choudhury (2005) stage 1 and 2 are combined. Here it is acknowledged that the gap acceptance stage is essential for modelling. In this research this applies as well. This is due the fact that looked will be at the merging at on-ramps only. In the Methodology chapter (6.1) more details on these conditions are disclosed.

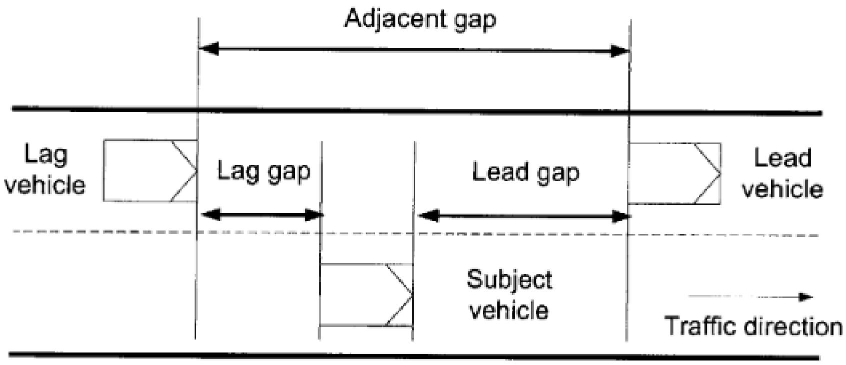

Figure 5.1: Potential lane changing situation where the gap acceptance model can be applied (Choudhury, 2005)

The gap acceptance model simulates the way drivers evaluate if a lane change can be executed safely and without hampering the vehicles on the new and old lane. Central is the question whether there is enough space to merge in the gap. The gap acceptance model assumes that the driver must accept both the lead gap and the lag gap to change lanes. Dependent on the velocity of traffic the adjacent gap shrinks or grows. Figure 5.1 shows a situation in which a lane change potentially could be made.

In their article Laval and Daganzo (2004) show that disruptive lane changes (DLC) are essential in explaining stop-and-go waves and the capacity drop phenomena. These DLC's tend to occur during synchronized flow and explain why a disruption on one lane the catalyst for a stop-and-go wave can be. It is reasoned that drivers often react with a merge when confronted with a slowdown in their current lane. It is common sense that a human driver would choose a faster driving lane comparing to one where a slowdown is happening. In synchronized traffic, often space is present to perform this discretionary or mandatory lane change, but it has effect on the target lane of the merging driver. The gap is in this case not sufficient to sustain string stability and action of following drivers is necessary. If this process is repeated for all lanes on a highway an all-lane stop-and-go wave is formed.

It is clear that sufficient space has to be present in front and behind the potential new position of a vehicle for a merge to ensure a non-congested state of traffic flow. As humans are not as accurate as automated vehicles potentially can be, disruptive merges still occur.

6. Conceptual Model

In the Chapter 2-5 the impacting factors of this study are explained. The goal of this thesis is to find an answer on the main question which is: ***To what extent can vehicles equipped with SAE-level 2 or SAE-level 4 influence or prevent stop-and-go waves formed at bottlenecks?***

Figure 6.1 shows the conceptual model depicting the steps of thought made in the research. As stated in Chapter 1.1 the focus on the research is on the impact of the three vehicle groups on disruptions on traffic when lane changing. These groups tend to have different behaviours with different rules when changing lanes. The expectation is that SAE-4 vehicles need less space to merge seamlessly when compared to human drivers. In what way LCA-equipped vehicles are in need of less or more space is unclear, a probable result is that due to their safety-central design actually more space is necessary to merge. This may increase the amount of perturbations in traffic and thus enlarge the possibility on the formation of stop-and-go waves.
A sub-objective is to study the impact of lane changing maneuverers on highway capacity. This study is not focussed on functions like ACC or CACC, but the fact is that high-level automated vehicles will be designed to reduce space headways and thus increase the capacity of a highway lane.

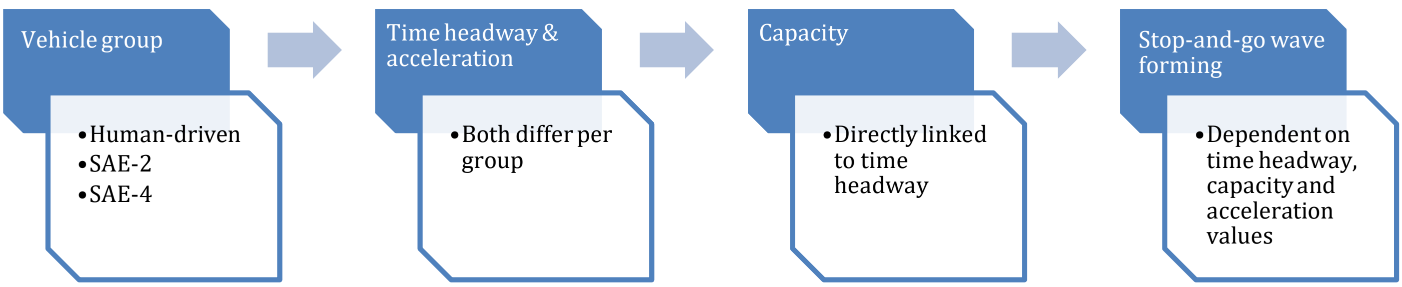

Figure 6.1: Conceptual Model of the research

7. Methodology

In this research the central method to gather outcomes is going to be a simulation. As SAE-2 and SAE-4 are not yet widespread used this is a great way to gather results about these vehicles and their relation to human-driven vehicles. A sizeable amount of articles which research AV's, lane changing, stop-and-go waves or a combination of these three tend to gather results with the help of microscopic simulations (Treiber, Hennecke & Helbing, 2000; Hidas, 2002; van Arem et al., 2006; Park & Smith, 2012). Figure 7.1 shows a schematic which can be seen as an example for the model created for this thesis.
Microscopic modelling, as the term suggests, is suitable to analyse the details of traffic flow. One desired goal is to model the formation and propagation of stop-and-go waves. For this cause, microscopic modelling is a just fit as the interactions taking place can be modelled in high detail (Mathew & Rao, 2007).

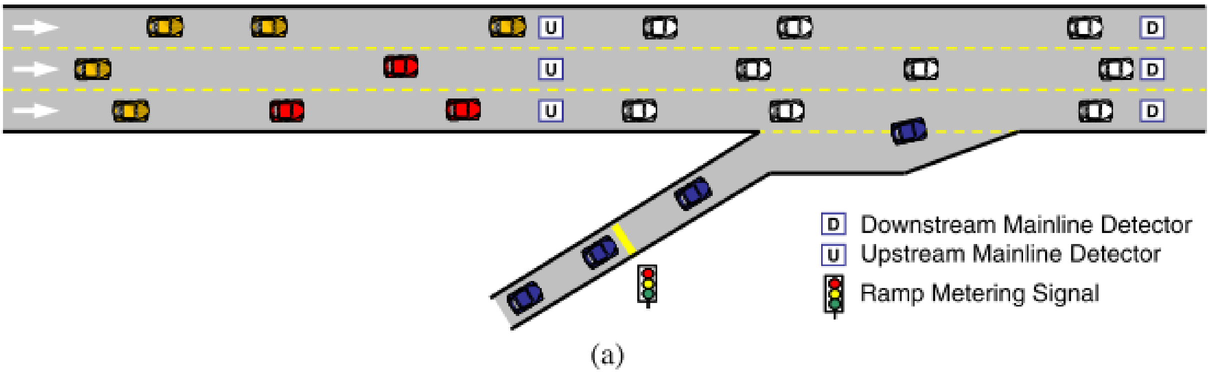

Figure 7.1: Schematic representation of a microscopic traffic model (Park & Smith, 2012)

These interactions will take place between the three categories present in the model:

- Non-automated human driven vehicles
- SAE-level 2 vehicles
- SAE-level 4 vehicles

7.1 Parameters and behaviour

For each of these categories, parameters are found which comply with their behaviour. This information is extracted from literature. Many of the parameter values can be found for the human-driven and SAE-4 vehicles. Articles which studied human lane changing behaviour are a great source for the first category (Ahmed, 1999; Choudhury, 2005; Ahammed, et al., 2008; Shladover et al., 2012, Zhao et al., 2017).
High-level automated vehicles are studied as well. Articles by Kesting et al. (2007) Vander Werf et al. (2002), van Arem et al. (2006) and Shladover et al. (2012) provide insight in how SAE-4 vehicles could behave.
Research that focusses on SAE-2 vehicles and Lane Change Assistance is less widespread. This can potentially make the validation of this category's behaviour difficult. Only a few studies are aimed at researching the broad concept of ADAS where LCA belongs to. The article of Kala and Warwick (2015) is an example which can help design and validate the behaviour of the LCA-vehicle group. Calvert et al. (2017) also have an overview with values that are often used in research for the SAE-2 group.
Table 7.1 shows which parameters are to be used to model the behaviour of the three vehicle groups.

Table 7.1: Variable parameters defining each vehicle group's behaviour

Parameter	Description	Human-driven	SAE-2	SAE-4
a,max	Maximum acceleration	**1.25 m/s²**	**2 m/s²**	**2 m/s²**
v0	Desired speed	120 km/h = 33.3m/s	120 km/h = 33.3m/s	120 km/h = 33.3m/s
s0	Min distance to leading vehicle at standstill	5 m	5 m	5 m
T	Headway behind SAE-0/2 vehicle	**0.5-1.5s**	**1.2-1.8 s**	**1.1 s**
TSAE4	Headway behind SAE4 vehicle	**0.5-1.5s**	**1.2-1.8 s**	**0.6 s**
bcomf	Comfortable deceleration	3 m/s²	3 m/s²	3 m/s²
bmax	Maximum deceleration	-8 m/s²	-8 m/s²	-8 m/s²
alfa	Sensitivity value	4	4	4

Essential in the model is the T parameter. T represents the preferable time headway a vehicle drives behind its predecessor. Human-driven vehicles are set to a time headway between 0.5 and 1.5 seconds. There is a sizeable discrepancy between drivers on the road and in the model random values between 0.5 and 1.5 seconds are used. According to Knospe, Santen, Schadschneider & Schreckenberg (2004) and Treiber, Kesting & Helbing (2006b) these are the time gaps preferred by human drivers. These time headways lead to a capacity of 3600 which is higher than the present capacities of 2100 vehicles per hour. This is due to the fact these time headways are the desired gaps. In real traffic vehicles are often in platooning groups. Between these groups bigger gaps are observed. This was hard to implement in the model and chosen is to work with the desired time gaps observed in traffic. In these traffic conditions the stop-and-go waves form, so are these researched.

SAE-2 vehicles have a T-headway between 1.2 and 1.8 when driving behind another vehicle. Recent studies' focus was mainly on this range (Vander Werf et al., 2002; van Arem et al., 2006; Kesting, et al., 2007; Shladover et al., 2012). As drivers are able to choose their preferred time gap it is hard to say which of these values will be used the most. Therefore was chosen for random values in this 1.2-1.8 range.

For the SAE-4 vehicle group the choice was made to set a 1.1 second distance from non-SAE-4 vehicles as this is closer than SAE-2 vehicles are able to drive. SAE-4 is expected to be more sophisticated than SAE-2. A striking element of this specific model is the change of T-headway values of SAE-4 vehicles when driving behind a vehicle of this same group. SAE-4 vehicles are equipped with CACC which decreases the vehicle gap. At this moment vehicles would communicate which allows a lower T-value. This communication is not present in the model but represented by the lowered time headway. 0.6 seconds is the chosen time headway. Due to communication between the vehicles string stability is still ensured with this value (Ploeg et al., 2011). Vander Werf et al. (2002) also set the time headway value on 0.6 on their research to capacity enhancements with ACC and CACC.

Another parameter which is different between the vehicle groups is the acceleration value. One reason why stop-and-go waves tend to form and propagate is the way humans accelerate after escaping the wave. Many drivers only accelerate only with 1.25 m/s². SAE-2 and SAE-4 would probably be designed with a maximum acceleration of 2m/s². This value can potentially help dispersing stop-and-go waves while preserving comfortable conditions. In the article from Calvert et al. (2017) this difference also was applied. In this research a look will be given if stop-and-go waves do or do not disappear due to this change in maximum acceleration.

Besides parameters for the behaviour of the three vehicle groups are set values needed for constant elements in the model. For instance, the length of the on-ramp influences the speed of merging vehicles. The merging velocity can impact the way how human drivers, and probably non-human drivers, switch lanes. Other fundamental elements are the preferred driving speed per lane, length of an on-ramp and so the maximum time reserved for a lane change and the amount of lanes. Table 7.2 shows the set values.

Table 7.2: Constant highway elements used in the model

Highway element	Set values	Source
Number of lanes	1 on highway, 1 on-ramp	N. A
Length on-ramp	200 meters	ANWB (2018)
Maximum speed	120km/h	Rijkswaterstaat (2018b)
Speed on on-ramp	Same speed as currently driven on highway	N. A

7.2 Data provision

The crux of modelling is to simplify reality in a way that the relevant factors of the studied phenomena are still observable. Including a lot of parameters influencing traffic flow would be 'realistic' but would make the model too complex. Adding a lot of parameters with little impact per parameter would make validating a near impossible task as well. Examples in literature showed which parameters could be of significant impact for this research. By experimenting with different sets of parameters and performing sensitivity analysis during the modelling process an overview of the significant factors will arise.

7.3 Modelling environment

With enough examples of microscopic models and parameters found, a start will be made on the building of the microscopic traffic model. Which software is the most suitable for this cause is debateable. Clear is that a software package should be able to create microscopic models. Software which is designed for creating macroscopic models (i.e. VISSUM) does not fulfil this need. Packages which do have the feature to create microscopic simulations are PARAMICS, MATSIM, MATLAB and SUMO. On ResearchGate the latter two are said to be free and supported by helpful communities (ResearchGate, 2018). PARAMICS is a commercial package which makes it a less desirable option. Eventually the choice has been made to start working with MATLAB, partly due to the license that the University Utrecht offers. Online multiple examples of traffic simulations made with MATLAB are present (Nezafat, 2014). These are used as examples to help create the model in this thesis. Another reason for this choice is the familiarity and experience with the software of supervisor Simeon Calvert. It is not unusual to involve MATLAB in this research field as Fernandes & Nunes (2012) and Zhao et al. (2017) and many others show.
In MATLAB are already some traffic models present. These models are the base of the lane changing model to be built for this thesis. Because of the lack of experience from the researcher's side, some exercises were needed to get used to MATLAB and be able to insert new lines of programming to these base models. Time was reserved for gaining experience with the software. Again, online there are enough possibilities available to do so.

7.4 IDM

The model chosen as base for this thesis is the IDM model. The Intelligent Driver Model (IDM) is a relatively simple model designed for car following. It is a kinetic model which outputs an acceleration value based on speed and distance differences between a leading and a following vehicle. This acceleration is determined by (1).

(1)

$$\frac{dv}{dt} = a * \left[1 - \left(\frac{v}{v0}\right)^4 - \left(\frac{s^*(v, \Delta v)}{s}\right)^2\right]$$

with,

(2)

$$s^*(v, \Delta v) = \mathrm{s0}\ + vT + \frac{v\Delta v}{2\sqrt{ab}}$$

where a is the comfortable acceleration, v is the current speed, v_0 is the desired speed, s_0 is the minimum headway (at standstill), T is the desired time headway, Δv is the speed difference with the leader, s is the current distance headway and b is the comfortable deceleration. The IDM model has a maximum macroscopic capacity just below 1900 vehicles per hour and shows realistic shockwave patterns. If a reasonable capacity is desired, the time headway of the vehicles has to be lowered to unrealistic values (Schakel, Van Arem & Netten, 2010).

7.5 IDM+

Due to this low capacity threshold and the unrealistic values to fix this, IDM can be seen as an unjust fit. In corresponding research by Schakel et al. (2010), focused at dampening stop-and-go waves, an alternative is presented. By tweaking the formulas used by IDM an adapted version in created: IDM+. In this way reasonable capacity values are achieved. By splitting the formula in two with delineated segments for free flow and synchronized flow where interaction is key higher and realistic capacity values are reached. The acceleration is now determined by (3) which replaces (1).

(3)

$$\frac{dv}{dt} = a * min\left[1 - \left(\frac{v}{v0}\right)^4, 1 - \left(\frac{s^*(v, \Delta v)}{s}\right)^2\right]$$

The division in the segments which define acceleration in free flow or 'interaction terms' is clearly visible in the graph visualizing flow versus the density of cars in the models. Figure 7.2 shows the

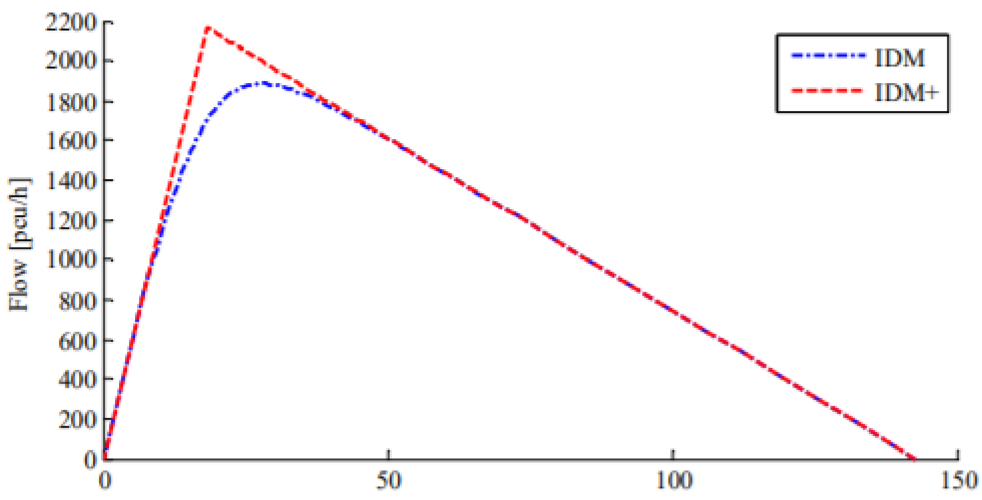

Figure 7.2: Flow-density equilibrium of IDM and IDM+ (Schakel et al., 2010)

equilibrium of the traffic flow and car density in a graph with v0 = 120 km/h, s0 = 2m, T = 1.45s and a vehicle length of 5m (Schakel et al., 2010).

The fact that IDM+ has more reasonable capacities when selecting the just parameters makes it more suitable for this research than IDM. It will be used as a basis on which the rest of the model will be built on.

7.6 Additions to IDM+

To get answers on the questions central in this research the IDM+ model alone is not enough. This basis is only one lane where vehicles, represented by points, follow each other. In essence is IDM+ a formula which calculates this; no visualizations are present here. To come to a model that embodies a main highway-lane and an on-ramp a few additions are done to the MATLAB-code. These additions include the spawning of vehicles on the main road, code for the merge of the vehicles, the behaviours of the vehicle groups and a 'controller' to determine the rates of human-driven, SAE2 and SAE4-vehicles driving on the main road and on-ramp.

7.6.1 Spawn criteria of main road vehicles

In the simulation setup it is determined how many vehicles are on the highway lane. The first vehicle is spawned at x=0 and belongs to one of the three vehicle groups. The rates of these groups are dependent on the values given in the code. How this works is described in Chapter 7.6.2. Every vehicle that follows is 40 meter behind its leading vehicle, but with somewhat stochasticity applied to this value. With a random number generator some deviance is added of a maximum of 49.5 meter. In this way the gaps between vehicles are different which will affect the merging later in the simulation. For now, this results in a capacity of 3000 vehicles per hour on the main lane. Thereby does the on-ramp provide a vehicle every 5 seconds. If every 5 seconds a vehicle is driving by this means that the capacity of the on-ramp is 720 vehicles per hour. Thus, after the traffic of the on-ramp is merged on the main lane 3720 vehicles are passing per hour.

7.6.2 Controlling the rates of vehicle groups

To research the effect of different rates of human-driven, lane-assistance and automated vehicles on capacity and stop-and-wave forming a piece of code is added to the model which controls these rates. This 'controller' is necessary to create the different scenarios. Before a simulation run is executed, key is to change these values to the rates to be researched. If we were to research the effect of 50% of SAE4 vehicles next to 50% human-driven vehicles the code looks like this:

```
1. sae_distr = [0.5 0.5 1.0]; %cumulative distribution of the SAE-levels = 0; 2; 4
2. sae_level = [0 2 4];
```

Followed up by:

```
3. sae_idx = find(iAV_rnd(vi)<=sae_distr,1,'first'); %index SAE level
4. veh(vi).sae = sae_level(sae_idx); %assign SAE level
```

The cumulative nature of this piece of code shown at line 1 makes sure that in this instance no SAE-2 vehicles are added at the mix. Since this code is used for vehicles on the main road and on the on-ramp only human-driven and SAE-4 vehicles are spawned.

The greatest difference between the vehicle groups is in the T-values. T, which represents the time headway, is smaller in the SAE-4 group. This is because that these vehicles are not affected by reaction times and are in this way able to drive closer to their leading vehicle. The T-value for each group is visible in Table 7.1. One criterion that makes SAE-4 vehicles even more efficient is the fact that the T-value is changed when driving behind another SAE-4 vehicle. This reduced time headway represents the CACC-abilities of this vehicle group. The expectation that this implementation will increase the capacity while ensuring string stability. This should contribute to a more stable traffic flow and so less stop-and-go waves.

7.6.3 Merge of vehicles

What the IDM+ model does is creating a table of all the vehicles with so-called structures containing the speed, acceleration and location for each timestep of 0.1 seconds. If there is chosen to run the model with 20 vehicles the product is a table with the same number of rows. These are in order in which the vehicles move downstream the highway-lane. Thus, the first indexed vehicle leads the rest. When a car merges this list will be split. In the space which was created with this split a merging vehicle will come in. Before this is done the movement of the vehicles on the main highway-lane are calculated. At every timestep the new acceleration, speed and position of the vehicles on the main lane are simulated. After this calculation the new position of the potential merging vehicle is simulated with the IDM+ formula.

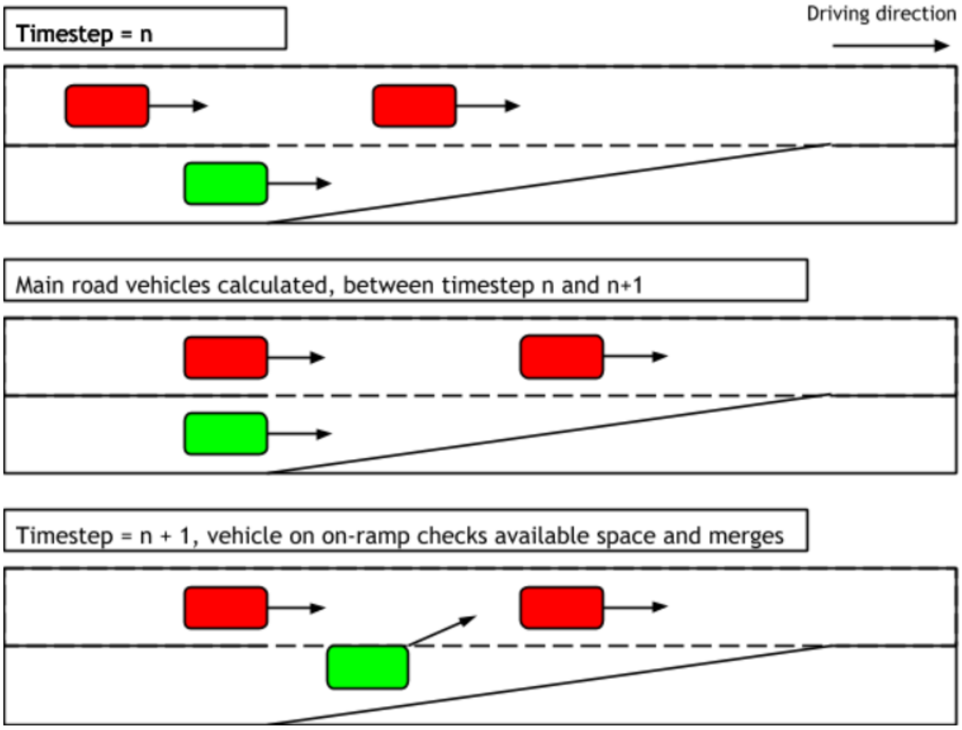

Figure 7.3: Representation of methods used for merging in the model

Subsequently a check will be performed if enough space is present to merge. The model will check if there is enough space is present between the potential leading and following vehicles on the main lane. The necessary space is expressed in time headway of the potential merging vehicle is behind a leading vehicle. This time headway is different per vehicle group. Table 7.1 shows that SAE-4 vehicles need less time headway to merge since human reaction time is eliminated by the automation of the vehicle.

To prevent vehicles of merging direct in front or at the same position as a following vehicle, which represent dangerous situations and collisions, code was added which ensures that this does not happen. Vehicles on the on-ramp are only allowed to merge if they are at least 0.6 seconds in front of a vehicle on the highway. The mergers must fulfil this and the headway condition to be allowed to merge. If these conditions are not met, this is tried again the next time step. Every potential merging vehicle has 60 time steps, which is the equivalent of 6 seconds, to find a suitable gap to merge. These 6 seconds correspond with the length of the on-ramp while driving 120 km/h. If these 60 time steps are over a mandatory merge is done. Here no conditions like the one described above have to be met, so situations occur where close wave-forming merging (and near-collision) maneuverers are done. Expected is that in a lot of cases the self-driving vehicles can find a merge gap before these detrimental mandatory merges are taking place. This would lower the amount of mandatory lane-changes which can disrupt traffic and so reduce the chance on the formation of stop-and-go waves.

The conceptual design of the model (see Appendix 2) included a politeness element. In some cases, this would have made merging easier. Yet it was hard to define what this politeness factor does and in which cases it would make sense. It was also the question if SAE2 and SAE4 vehicles would be designed as perfect and polite traffic participants. By including this as an assumption, the validity of the model would only decrease so the choice was made is to leave out this element of politeness. Figure 7.4 shows the steps made in the model.

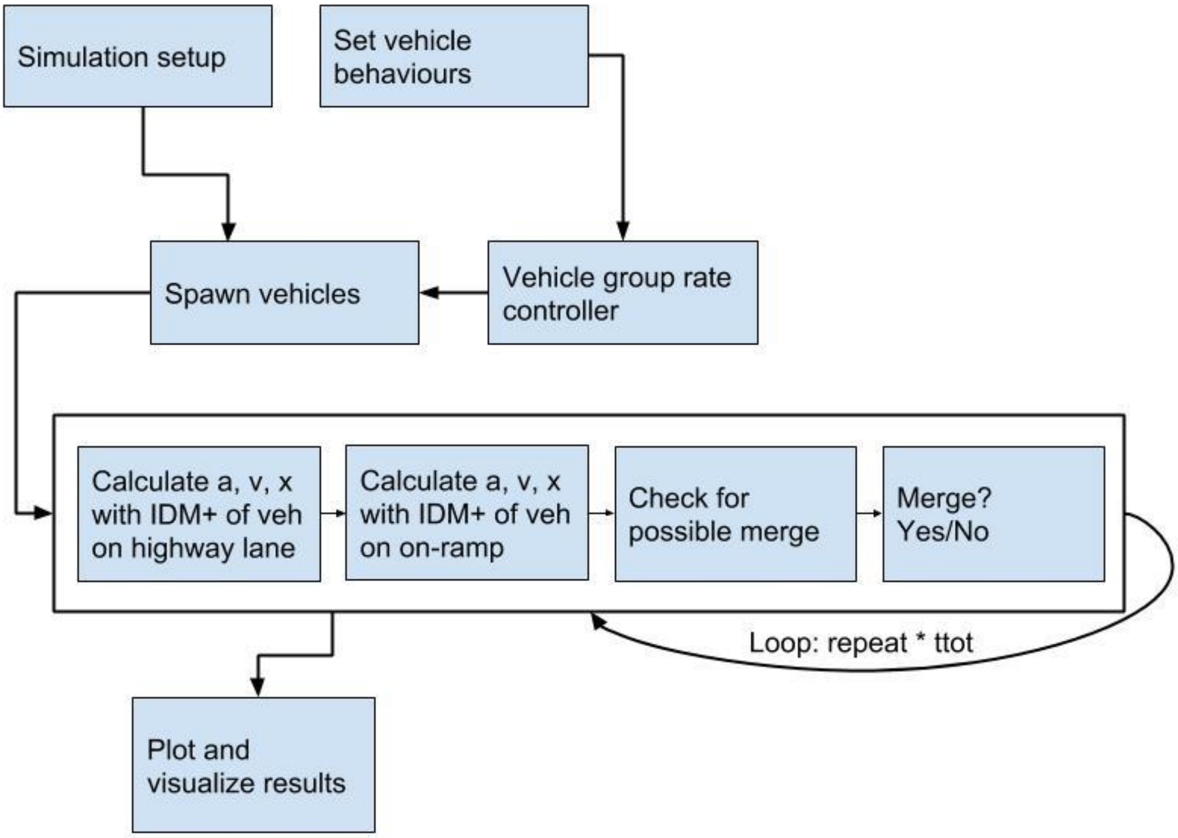

Figure 7.4: Steps made in the model

7.7 Verification and validation

During the model building process parameters and pieces of code were altered to ensure a verified and valid model. If the 7.5 chapter is compared with the design shown in Appendix 2 the similarities and differences between the designed and used model are shown.
Another check is necessary to verify if the model represents what it is intended for. In the case of this thesis is a model expected where for instance stop-and-go waves are created when 100% of the vehicles are human-driven. Also, realistic values comparable with the examples should be in place.

7.8 Sensitivity analysis

A sensitivity analysis has the goal to check what the sensitivity of the model is when some key parameters are altered. Differences will be applied to the length of the merging lane, maximum and so desired speed of the vehicles and spawning distances between vehicles. The ratios of the three vehicle groups will be altered as well but as this last point is central for the results and will show the effect of ADAS-equipped and autonomous cars on traffic flow and capacity. Because of this it will be in the central segment of the results chapter.

Table 7.3: Selected parameters for the sensitivity analysis

Parameter	Description	Value in standard model	Sensitivity range	Steps made for analysis
xmerge/ maxMergeDur	Length on-ramp / maximum time to merge in time steps	200m/ 6 seconds	100-500 meters/ 3-15 seconds	Every 100 meters/ 3 seconds
v0	Desired speed	120 km/h	100-140 km/h	Every 10 km/h
ds_default	Default distance between vehicles at spawn	40 meter	20-60 meter	10 eter

7.9 Defining scenarios

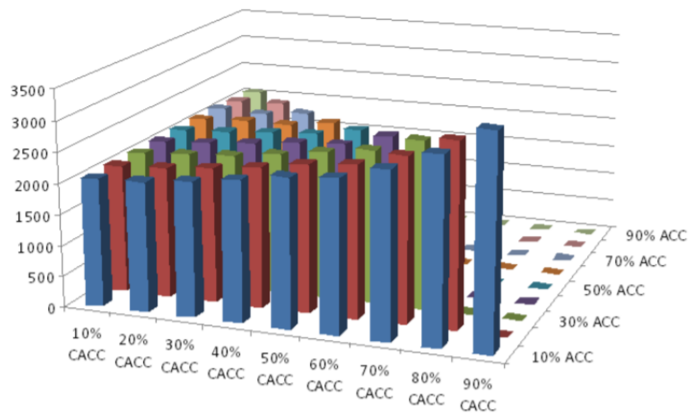

Figure 7.5: Prediction of Lane Capacity Effects of ACC and CACC (Shladover et al., 2012)

In the literature it is clear that penetration rates of automated vehicles greatly determine if positive or negative effects are expected to take place. To which group these vehicles belong, is besides this penetration rate of great impact as well. Together are these factors responsible for what happens on the highway. A structured way to research these altering factors is by running the model on different rates of human-driven, SAE-2 and SAE-4 vehicles. An example in literature is the research by Shladover et al. (2012). In this article 45 different combinations of penetrations are studied. Each combination is unique, and steps are made of 10% more ACC or CACC penetration per set. Figure 7.5 shows the increase of capacity when ACC and CACC rates go up.
To study exactly what happens in all these combinations can considered as time-consuming. Therefore, the choice was made to create an overview by looking at the potential capacity and probability of stop-and-go waves forming in a similar fashion as the example of Shladover et al. (2012). By sticking to combination with different rates which differ 20% per set, 21 sets are researched.

7.9.1 Base scenario

For a more in-depth analysis a few scenarios are in place. First the results of the base model with 100% human drivers will be presented. How does this hold up with reality and how does the stop-and-go wave pattern unfold are central in this base scenario.

7.9.2 2030/2035 scenarios

Calvert et al. (2017) estimated what percentages of vehicles will be ACC/LCA and CACC equipped in the near future. Figure 4.3 shows these percentages. The two estimations which really pop up are the 2030 and 2035 years. Here big steps towards sizeable percentages of SAE-2 and connectivity are made. Of course, some uncertainties come up with estimations for situations which will occur in more than a decade, but it will be interesting how the traffic flows and capacity of highways will differ in this period in time.

7.9.3 100% scenarios

Table 4.1 showed that researchers tend to research the full implementation of ACC and CACC. Results differed in these researches. These divergent results are due to different methods. Interesting will be what the results will be of the methods used in this thesis. Thus, the 100% SAE-2 is looked at for the ACC results. 100% SAE-4 results will be compared with the CACC values in other researches.

Besides these scenarios looked will be what the tipping points are. The hypothesis is that the connected nature of SAE-4 vehicles will lower the time headway around 17% penetration. Around this point the positive effects of the platooning could generate a higher capacity than the base model. Also, a look is given to which exact penetration stop-and-go waves disappear.

8. Results

The previous chapter presented an overview of the choices made concerning the model. This resulted in a base model, that is easy to modify to create the different scenario's and perform a sensitivity analysis.

8.1 Base scenario

Now that the methods are clear it is time to run the base model and analyse it. Table 8.1 shows a complete list of parameters directly influencing the model. Values in black cursive have differences between the vehicle groups.

Table 8.1: Core parameters influencing the model

Parameter	Description	Human-driven	SAE-2	SAE-4
a,max	Maximum acceleration	**1.25 m/s²**	**2 m/s²**	**2 m/s²**
s0	Minimum distance to leading vehicle	5 m	5 m	5 m
T	Headway behind vehicle	**0.5 – 1.5 s**	**1.2-1.8 s**	**1.1 s**
TSAE4	Headway behind SAE4 vehicle	**0.5 – 1.5 s**	**1.2-1.8 s**	**0.6 s**
Bcomf	Comfortable deceleration	3 m/s^2	3 m/s^2	3 m/s^2
Bmax	Maximum deceleration	-8 m/s^2	-8 m/s^2	-8 m/s^2
alfa	Sensitivity value	4	4	4
xmerge/ maxMergeDur	Length on-ramp / maximum time to merge in timesteps	200m/ 6 seconds	200m/ 6 seconds	200m/ 6 seconds
v0	Desired speed	120 km/h	120 km/h	120 km/h
mergeFreq	Frequency of merges in seconds	Every 5 seconds a new vehicle	Every 5 seconds a new vehicle	Every 5 seconds a new vehicle
ds_default	Default distance between vehicles at spawn	40 meter	40 meter	40 meter

Striking about the chosen values is the difference in the time headway between humans and the automated vehicle groups. Humans have a random headway between 0.5 and 1.5 seconds. The mean is 1 second. SAE-2 vehicles have a mean of 1.5 and SAE-4 have a headway of 1.1 seconds. Both automated vehicles groups need more distance to a leading vehicle than the human group does, except when a SAE-4 vehicle follows another SAE-4 vehicle. This represents connectivity between the CACC-equipped cars. Another value which differs between these groups is the acceleration value. Maximum values of 1.25 seconds for the human-driven vehicles and 2.0 for the automated groups. This should have effect on the formation and propagation of the stop-and-go waves. This is due that humans aren't able to accelerate quickly away from traffic jams. The consequence is that following drivers do not have the space to accelerate more freely. When the base model, with only human drivers, is ran, it produces a table with acceleration, speed and position values per time step. With this extensive table, calculations are possible to see what the average speed is, how much time is spent in traffic jams and what the speed is of this stop-and-go wave. Besides is this information used to create graphs. The graph in which stop-and-go waves are immediately recognized is shown in Figure 8.1.

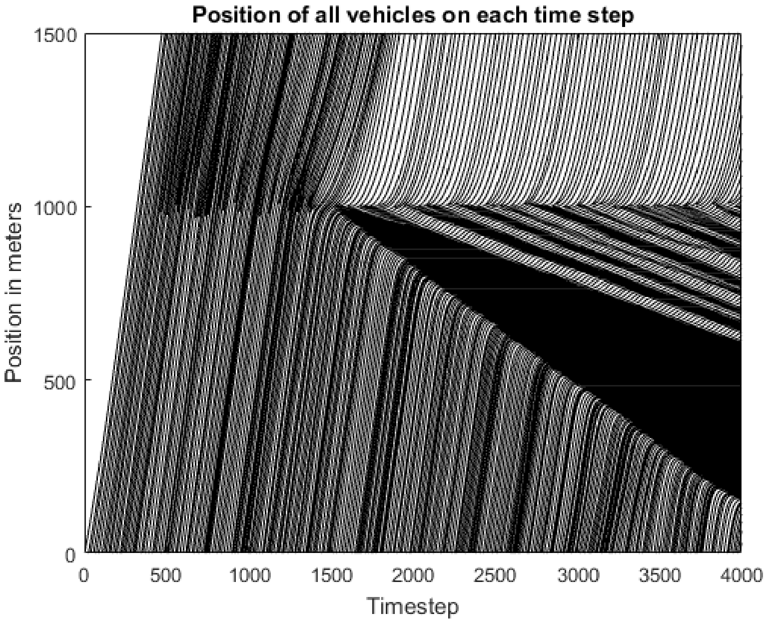

Figure 8.1: Position vs time steps with 100% human drivers

In this graph, the position of vehicle (x) is plotted against the time steps in the model. One time step correspons with 0.1 second. Around 1000 meters and 400 time steps the first merging vehicle succeeds in merging in. This vehicle is followed by multiple vehicles before the first stop-and-go wave starts to form. A threshold is reached where the capacity is too high. This tipping point is around time step 1500. Cars don't have the space to drive at high speed when merging vehicles come in. The first vehicle comes to a complete stop and so do the following vehicles. In this model the stop-and-go waves move upstream at 7 km/h. This is clearly slower than the 15 km/h in the article of Laval and Leclercq (2010). Striking is the fact that a stop-and-go wave is followed up by another one as happens in reality. These waves would go on for ever as there is no position on the highway with a lower influx of vehicles. The simulation is stopped at time step 4000 to limit the process time and size of the output. Therefore, the stop-and-go waves stop here, as does all traffic.

Vehicles are able to have negative x values. A few things happen before the merging vehicles are brought in. Figure 8.2 is a zoomed out plot of the output of the base model. Clear is the spawn of almost all vehicles at time step 0. Here they start driving with 120 kilometres per hour. Almost no slowdowns are seen in this part of the output. One other stop-and-go wave is created on this highway. Due to an overflow of vehicles due to relative small time headway values a wave forms at x= -8200 at time step 1700. Here vehicles are part of a phantom jam created due to an exceedance of the capacity value with this vehicle mix of 100% human drivers. It should be noted that in the calculations of time spent in stop-and-go waves this particular wave is excluded. Ultimately the choice was made to calculate the results for the first 413 vehicles. In this way the wave around x= -8200 is not included and only waves around the on-ramp are considered.

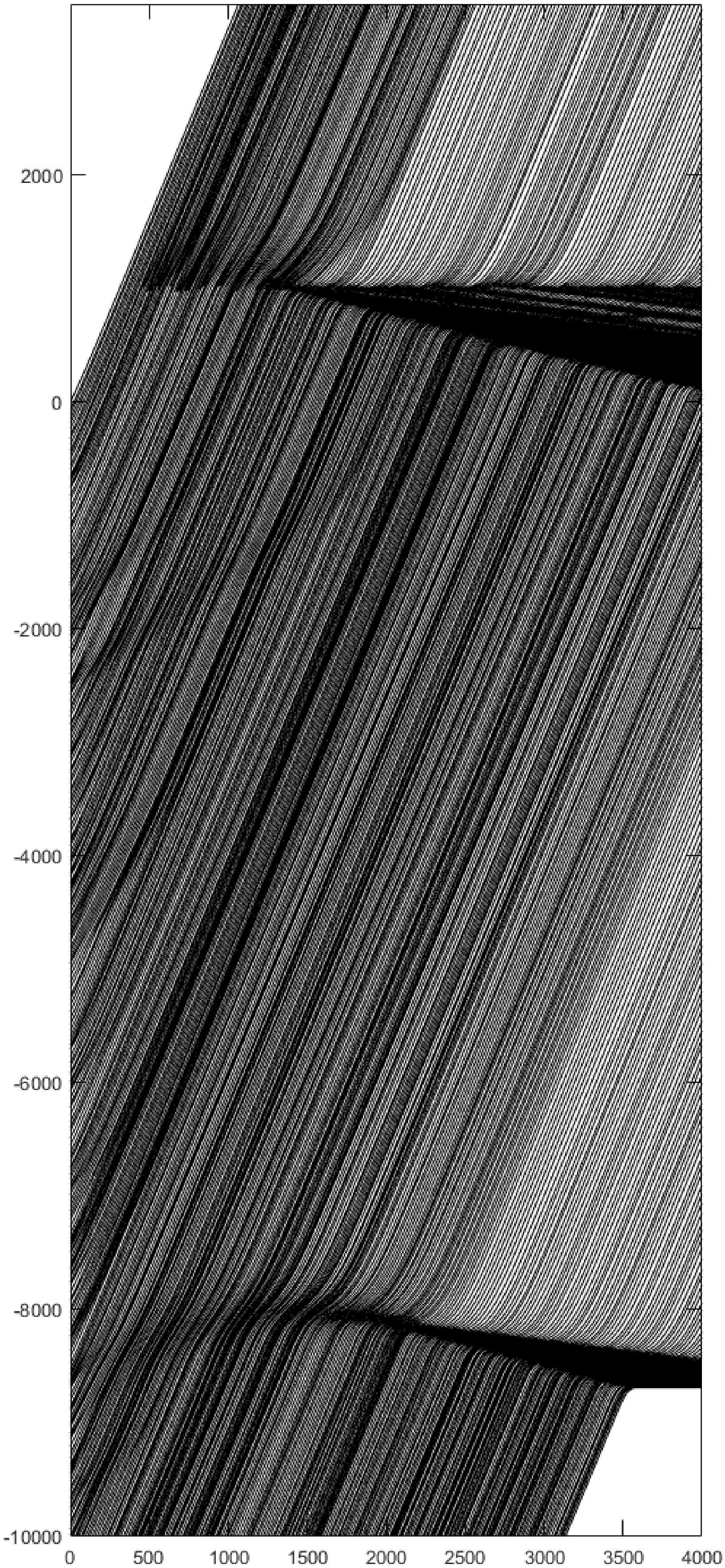

Figure 8.2: Position vs time steps with 100% human drivers (X_-10000: X_3000)

Thus, in total 413 vehicles are modelled. For 4000 time steps the acceleration, speed and position is calculated. Not all vehicles exist at the first time step, as 74 vehicles are merging in later. In total 1.652.000 data points per output variable are created. Of these points 1.494.281 correspond with a spawned vehicle. 234.137 of the data points corresponding speed have a value below 6,94 meters per second (6,94 m/s = 25 km/h). This means that according to the measure methods of Rijkswaterstaat (2018a) in this base model 15,7% of time is spent in stagnant traffic. Of these 234.137 time steps 171.595 have a value of 0. Thus, 11,5% of the total time was spent in total standstill.

When we look at Figure 8.2 it does not seem like vehicles are standing still 11.5% of the time. This is due to the difference in denseness between the stop-and-waves and synchronized flow. The minimum distance to a leading vehicle is 5 meters. Vehicles do not have a length so this 5 meter is from point to point, which is the equivalent from front bumper to front bumper in real-life.

In the 84.3% of time in which vehicles are able to drive faster than 25 km/h often the maximum desired speed of 120 km/h is reached. 79.01% vehicles can drive above the 90 km/h. Due to this high percentage of near maximum speed driving vehicles the average speed driven in the base model is 96.9 km/h.

As it is interesting to see what manoeuvres are happening in the model an indicator for this is in place. It is hard to say which lane changes are disruptive and which ones are not, another output is necessary to measure the formation of the stop-and-go waves. The model works with comfortable and maximum deceleration. Every vehicle wouldn't brake harder than 3 m/s if not necessary, but in some situations drivers have to. By looking to the amount of time steps that vehicles brake more than 3 m/s^2 an indicator for disruptive manoeuvres is present. In this way we look at the reaction of following vehicles on the eventual disruptive lane changes of their predecessors. In the base model 0.98% of the decelerations are "uncomfortable".

Scenario	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of uncomfortable decelerations	Occurrence of stop-and-go waves?
Base	96.9 km/h	15.7%	11.5%	79.01%	0.98%	Yes, only at the on-ramp

Table 8.2: Core results of the base model

The values of Table 8.2 are to be compared with the results from the different scenario's described in 7.9. This will be done in chapter 8.3. First the sensitivity analysis is presented.

8.2 Sensitivity analysis

To check and prevent extreme and/or unforeseen results when running the model, a sensitivity analysis is in place. Table 7.3 shows which parameters are altered. One goal of the sensitivity analysis is to check if the chosen values in the base model are just. Other values can disrupt the stop-and-go waves or create waves at non-merging locations. Per parameter a few results which are influenced are compared. For example: the length of the on-ramp will probably affect the amount of disruptive lane changes.

8.2.1 Length on-ramp

The standard length of an on-ramp in the Netherlands is 200 meters, but there are examples of longer on-ramps. For the completeness a look is also given to an on-ramp of 100 meter. Table 8.3 shows which lengths of on-ramp were looked at. Expected is that in real-life a longer on-ramp would create more time for merging vehicles to find a suitable spot to merge. The different lengths of on-ramps showed that in this model this does not occur. Drivers on the on-ramp do not have the ability to drive strategically. By this is meant that they are not able to accelerate or decelerate to drive next to a more suitable spot. Instead vehicles tend to drive at the same velocity as the vehicles in the main lane did on the first time step the merging vehicle appeared. Besides no politeness factor is included in the model and thus vehicles on the main road do not make space for mergers. This would make more space on an on-ramp probably more effective.

Table 8.3: Results of different lengths of on-ramp

Length on-ramp	Average speed	Percentage of uncomfortable decelerations	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Occurrence of stop-and-go waves?
100 meter	95 km/h	1.1%	17.0%	13.2%	Similar to base model
200 meter (base scenario)	96.9 km/h	0.98%	15.7%	11.5%	Yes
300 meter	95 km/h	1.1%	17.3%	13.9%	Similar to base model, first wave grows
400 meter	98 km/h	1.2%	15.1%	13.1%	Similar to base model, first wave grows
500 meter	96 km/h	1.2%	16.1%	14.1%	Similar to base model, first wave grows

A look at these results tells that longer on-ramps do not influence the formation of stop-and-go waves. A longer on-ramp does not mean less disruptive lane changes and thus less stop-and-go waves and so doesn't a shorter lane result in more traffic waves.
What does happen is an expansion of the first stop-and-go wave. When comparing base scenario (Figure 8.1) with a run of the model with an on-ramp length of 500 meter (Figure 8.3) clear is that the size of the first wave differs. This is not incorrect, but the preference is present to study multiple waves following each other. The base model is more suited for this preference.

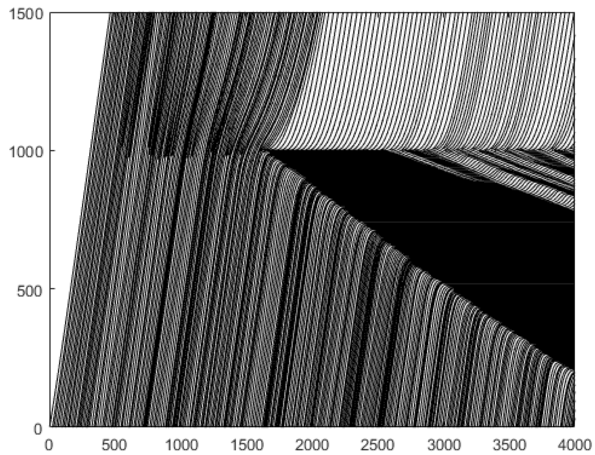

Figure 8.3: Position vs time steps with 100% human drivers. On-ramp is 500 meters.

8.2.2 Maximum and desired speed

All vehicle groups have the desire to drive at maximum speed. In the base model chosen is for a maximum speed of 120 km/h. This speed is often found on busy Dutch highways. 100 and 130 km/h are also standard maximum speed limitations. As table 8.4 shows are speed values of 100 to 140 km/h part of the sensitivity analysis. Expected was that higher speeds would raise the average speed, but also would impact the amount of wave forming actions. This expectation can be considered as true. Higher maximum speeds result in bigger differences between merging vehicles and vehicles on the main lane. Due to this the amount of time spent in uncomfortable decelerations increases when the maximum speed is increased as well. The increase of 20 km/h between 120 and 140 km/h results in almost twice as much uncomfortable decelerations.

Table 8.4: Results of different maximum/desired speed limitations

Maximum speed	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of time in uncomfortable decelerations	Occurrence of stop-and-go waves
100 km/h	87.8 km/h	10.9%	7.2%	84.4%	0.63%	Yes, but less strong than base model
110 km/h	91.9 km/h	14.6%	10.7%	81.9%	0.83%	Yes, but less strong than base model
120 km/h (base scenario)	96.9 km/h	15.7%	11.5%	79.0%	0.98%	Yes
130 km/h	98.6 km/h	15.8%	12.0%	74.2%	1.34%	Yes, more waves appear before on-ramp
140 km/h	100.1 km/h	17.2%	12.3%	71.3%	1.80%	Yes, more waves appear before on-ramp

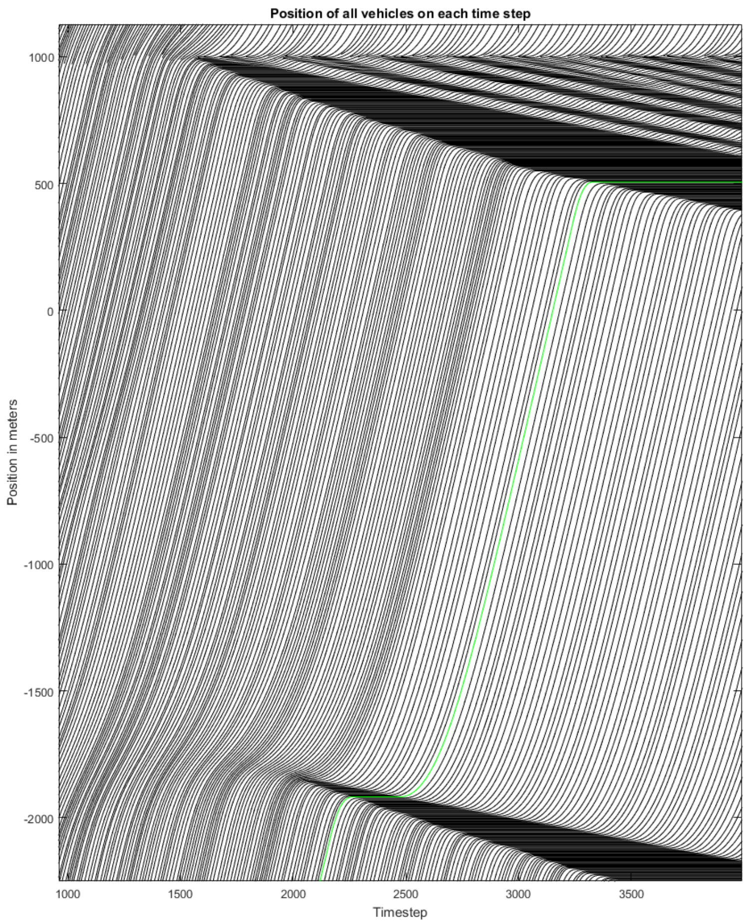

Figure 8.4: Position vs time steps with 100% human drivers. Maximum speed is set at 140 kmh. The green line is one vehicle encountering two stop-and-go waves.

Albeit that more stop-and-go waves are observed in the highways with higher maximum speed, the average speed also increases. More and longer slowdowns are present, but the periods when vehicles are outside these slowdowns higher speeds are reached. Striking is that the amount of time spent above 90 km/h decreases when the maximum speed is increased. This time is spent in stagnant traffic or standstill.
Figure 8.4 shows that if the maximum speed is increased to 140 km/h vehicles are driving from wave to wave with high speeds. The green line is a selected vehicle that spends a sizeable amount of time in stop-and-go waves but is still able to travel great distances. In the base scenario smaller distances are travelled without any standstills.

8.2.3 Default distance between vehicles at spawn

In this research the spacing of the vehicles is an essential factor for the occurrence of stop-and-waves. All vehicles are modelled to drive exactly 120 kmh. Due to this traffic keeps the same formation as at spawn. In the model lines of code are added to control this default spawn distance. Well to know is that a random element is added to create different distances between cars. With this randomness it is possible for a vehicle to spawn 25 meters closer or further than the default distance. For this reason, the two first sensitivity scenarios result in a lot of slowdowns; the vehicles spawn close after or in front of their predecessors. Besides correspond these spawn distances to capacities of 6000 and 4000 vehicles per hour, which are impossible to find in real life with human driven traffic.

Table 8.5: Results of different default distances of vehicles by spawn.

Default distance between vehicles at spawn	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of time in uncomfortable decelerations	Occurrence of stop-and-go waves
20 meters	62.4 km/h	35.1%	26.6%	40.9%	2.42%	Yes, waves also form after spawn
30 meters	73.2 km/h	27.2%	20.3%	50.9%	1.98%	Yes, waves also form after spawn
40 meters (base scenario)	96.9 km/h	15.7%	11.5%	79.0%	0.98%	Yes
50 meters	114.8 km/h	1.1%	0.5%	93.6%	0.13%	No, only small fluctuations
60 meters	119.3 km/h	0.0%	0.0%	99.7%	0.00%	No, no slowdowns are formed

Due to the fact that the spawn distances of 20 and 30 meters are smaller than the time headways of human drivers stop-and-go waves start to happen right away. Only after vehicles have left these waves, speed and distances are back to the desired values until another wave is met. Figure 8.5 and 8.6 show the positions at each time step of vehicles for spawn distances of 20 and 60 meters respectively. The difference is clear; a small distance creates an unstable, crowded highway where waves form even on places where no on-ramp is situated. A relative higher value of 60 creates too much space between cars and does not result in the formation of waves. For this reason, it can be considered as unsuitable for the research. This is backed up by the results in Table 8.5.

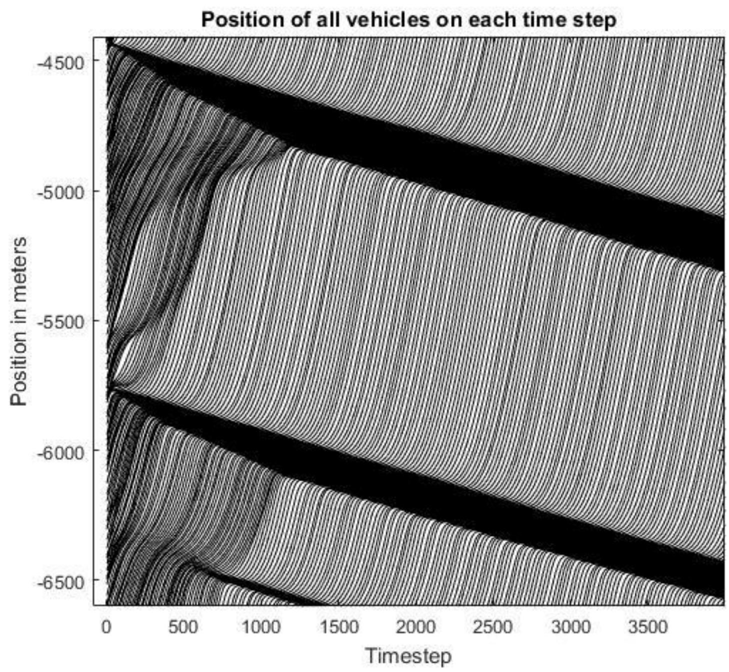

Figure 8.5: Position vs time steps with 100% human drivers. Default spawn distance is 20 meters. Waves form at the first time steps.

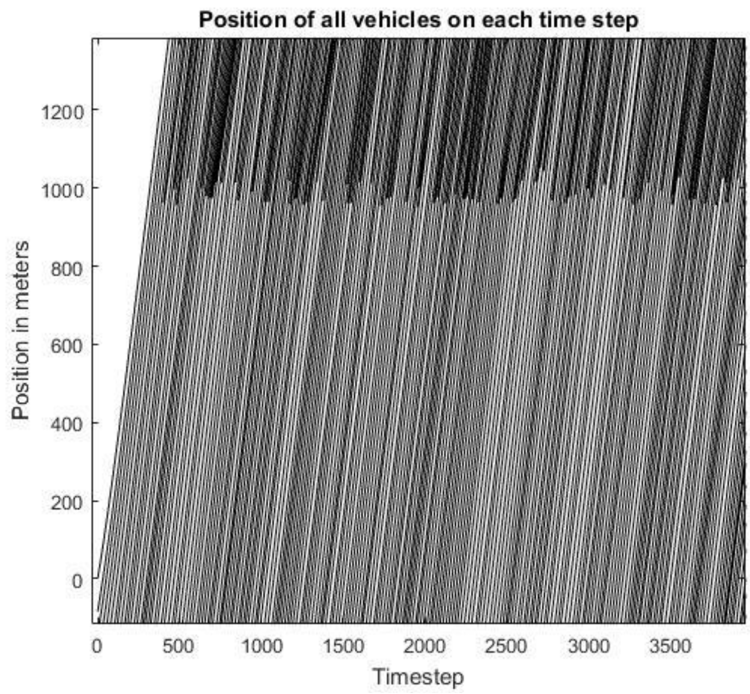

Figure 8.6: Position vs time steps with 100% human drivers. Default spawn distance is 60 meters. No waves form, even at the on-ramp location.

Altering the parameters which directly influence the model has shown that the balance in the model is delicate. Small differences show that stop-and-go waves can form at more instances than only at an on-ramp. This proves once again why the base model was chosen for the analysis.

8.3 Vehicle mix and capacity

The goal of this thesis is to research the effect of SAE-2 and SAE-4 equipped vehicles on the formation of stop-and-go waves. To research this the vehicle mix spawned on the main lane and the on-ramp in the model is changed. Table 8.6 shows which mixes are looked at in the analysis.

Table 8.6: Vehicle mixes looked at in the analysis

SAE-4	Percentage to share between SAE-0 and 2	SAE-0/2	SAE-0/2	SAE-0/2	SAE-0/2	SAE-0/2	SAE-0/2
0%	100%	100/0%	80/20%	60/40%	40/60%	20/80%	0/100%
20%	80%	80/0%	60/20%	40/40%	20/60%	0/80%	-
40%	60%	60/0%	40/20%	20/40%	0/60%	-	-
60%	40%	40/0%	20/20%	0/40%	-	-	-
80%	20%	20/0%	0/20%	-	-	-	-
100%	0%	0/0%	-				

In begin of the Results chapter (8.1) the base scenario is described and analysed. The outcomes of the different vehicle mixes are compared with this base scenario. The average time headway of this base scenario was 1 second as the time headway of human drivers has a random value between 0.5 and 1.5. This would correspond with a capacity around 3.600 vehicles per lane per hour. This number is too high for a real-life highway, even for one without any freight trucks, but it can be used to compare. Vehicle mixes with SAE-2 and SAE-4 will have higher and lower capacities than this 3.600 vehicles per hour. The capacity values of these mixes are compared with the base scenario in Table 8.7. Figure 8.7 visualises this table.

Table 8.7: Capacity in vehicle an hour per vehicle mix

		SAE2					
		0%	20%	40%	60%	80%	100%
SAE4	0%	3600	3249	2968	2714	2555	2400
	20%	3605	3255	2946	2765	2582	
	40%	3704	3300	3075	2847		
	60%	4067	3738	3410			
	80%	4669	4087				
	100%	6000					

These results show a clear pattern, a higher share of SAE-4 equipped vehicles is companied with a higher capacity, while a higher share of SAE-2 equipped vehicles will drop this number. In Figure 8.7 this difference in capacity is easily recognizable.
Noted should be that these are theoretical capacities. Operational capacities are different in a few ways. Humans have the habit to drive in platoons. In these platoons the observed time gaps of 0.5-1.5 are present. Outside these platoons time headways are observed to be greater. Operational capacities for humans are lower in real-life than the theoretical ones calculated in this research, but it is hard to say how this will affect the capacities of the vehicle mixes with SAE-2 and SAE-4 included. It is hard to predict if these vehicles would be driving with or without creating gaps significant bigger than their time headways.

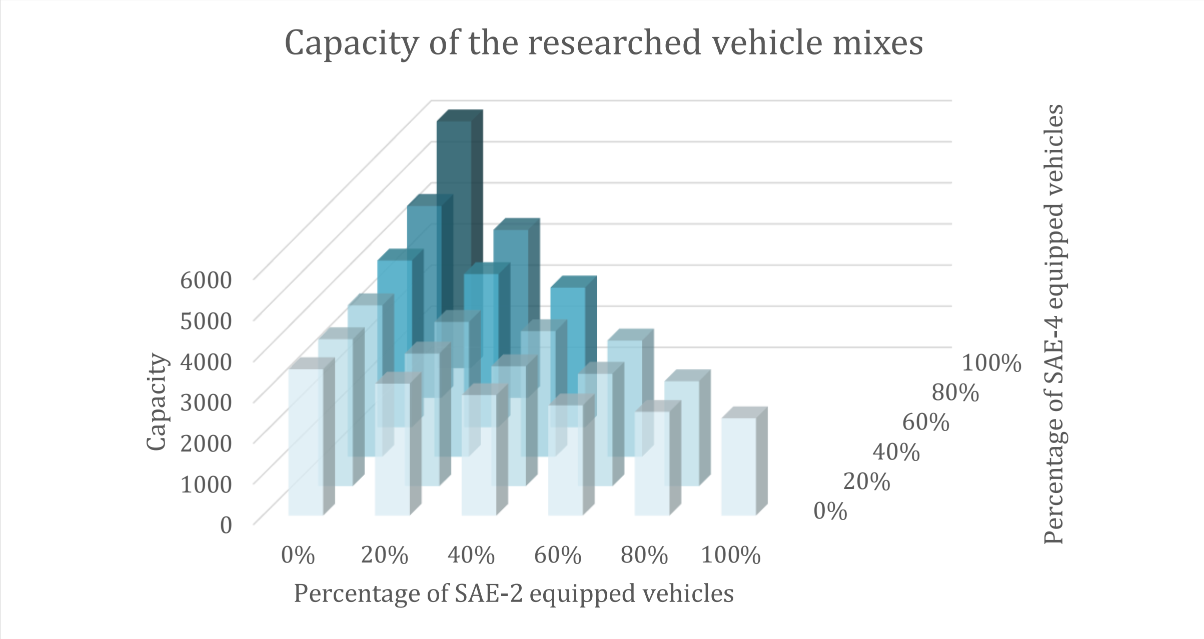

Figure 8.7: Capacity of the researched vehicle mixes

By plotting the vehicle mixes where SAE-2 and SAE-4 are only accompanied by SAE-0 vehicles this pattern is made visible. The capacity of SAE-2 drops per 20% step due to the longer time headway value of this vehicle group. SAE-2 vehicles in the model can have a random value between 1.2 and 1.8 seconds in which they keep distance to their leading vehicle. On average a SAE-2 equipped vehicle has a time headway value of 1.5. Human-drivers in the model keep a distance of 0.5-1.5 seconds. Individually some SAE-2 equipped vehicles drive closer to a leading vehicle, but on average humans need 0.5 seconds less when following. When the average time headway is 1.0 seconds, 3600 vehicles can pass in an hour. With an average of 1.5 this capacity drops to 2400 vehicles. In Table 8.8 shown is that every step of 20% increase the average time headway in that scenario with roughly 0.1 seconds. Inaccuracies are due to small differences in randomness of headway and vehicles shares. When these average time headways are converted to capacities patterns start to become visible; Figure 8.8 shows this.

Table 8.8: Average time headway for SAE-2 and SAE-4 shares. Remaining shares are human drivers.

Vehicle share	0%	20%	40%	60%	80%	100%
SAE-2	1.00	1.11	1.21	1.33	1.41	1.50
SAE-4	1.00	0.99	0.97	0.89	0.77	0.60

Figure 8.8 indicates that the workings of SAE-4 vehicles work differently than that of SAE-2 equipped vehicles. SAE-4 vehicles have a time headway of 1.1 when driving behind SAE-0 or SAE-2 vehicles. This is 0.1 slower of the 1 second average of human drivers. But when driving behind another SAE-4 vehicle, the time headway of these connected vehicles is decreased to 0.6 seconds. This connectivity starts to pay off when the percentage of connected SAE-4 vehicles start to grow. On the higher percentages platoons start to emerge in which multiple vehicles follow each other with a time headway of 0.6 seconds. Due to this, the average time headway drops greater at these steps than at the 20% and 40% scenarios. Where the line representing SAE-2 vehicles is linear, is the SAE-4 line logarithmic.

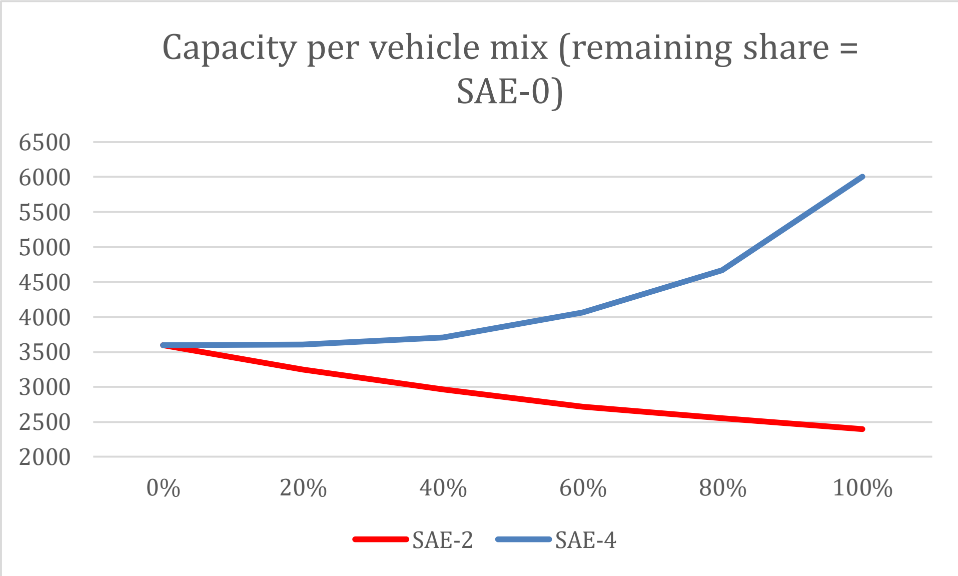

Figure 8.8: Capacity per vehicle mix (remaining share = SAE-0)

To compare the different vehicle mixes with the base scenario Table 8.9 is set up. Due to the optimistic average of 1 second that an average human driver as time headway has been assigned, the capacity of 100% SAE-0 vehicles is 3600 vehicles an hour.
In this table we see the same patterns made visible in Figure 8.8. But not only these vehicle mixes are modelled. The 10 other vehicle mixes show some relevant results as well. The capacity of the SAE-4 vehicle mixes rises more heavily in the latter scenarios. A consequence is that low penetrations of SAE-2 and SAE-4 vehicles, for example where both account for 20% of the fleet, are mainly influenced by the high time headway values of the SAE-2 vehicles. Therefore, the capacity drops with these scenarios.
Scenarios with high SAE-4 and low SAE-2 penetrations tend to have a positive effect on the capacity. Scenarios with low SAE-4 and high SAE-2 shares have a negative effect on capacity.

It is interesting to see that only after 18% the self-driving vehicles have a positive effect for the capacity. Due to the standard time headway of 1.1 when driving behind a non-SAE-4 vehicle the lowering of this value to 0.6 only comes up enough after the 18%.

Table 8.9: Percentage of difference between vehicle mixes and base scenario

		SAE-2					
		0%	**20%**	**40%**	**60%**	**80%**	**100%**
SAE-4	**0%**	N.A	-9.74%	-17.55%	-24.60%	-29.03%	-33.33%
	20%	+0.13%	-9.59%	-18.15%	-23.21%	-28.28%	-
	40%	+2.90%	-8.33%	-14.59%	-20.91%	-	-
	60%	+12.98%	+3.83%	-5.29%	-	-	-
	80%	+29.69%	+13.53%	-	-	-	-
	100%	+66.67%	-	-	-	-	-

With the chosen time headways capacity can potentially grow with 66.67% to 6.000 vehicles an hour. This is only reached when 100% of the vehicles are self-driving vehicles which can connect and communicate with other vehicles of the SAE-4 class. Vehicles who drive between the SAE-4 equipped vehicles break the platooning, which nullify the positive effects.

Increases in the amount of SAE-2 equipped vehicles are not positive for the traffic flow. If 100% of the vehicles would be equipped with lateral and longitudinal assistance the capacity can potentially drop to 2.400 vehicles per hour which is a 33.33% decrease.

8.4 Scenario results

In the Methods section (7.9) five scenarios were set up. In this section these will be compared. Central is the effect of the SAE-2 and SAE-4 vehicles on the formation and propagation of stop-and-go waves. The base scenario has already been discussed in the begin of the Results chapter (8.1). These results will be used for the comparison between the scenarios.

8.4.1 2030 scenario

Figure 4.3 showed that Calvert et al. (2017) expect that in 2030 25% of the vehicles will at least have ACC equipped. Of this 25% near half also have LCA as an option. Also, it is reasoned that 3% of the vehicles have CACC equipped and can be accounted to the SAE-4 group. For this scenario the vehicle mix is 25% SAE-2 and 3% SAE-4 vehicles. The remaining 72% of the vehicles is driven by humans.

When a look is given to the average time headway of this scenario it is clear that the 25% of the vehicles equipped with SAE-4 raises this number. The average time headway of the base scenario is 1 second. The average headway in 2030 will be 1.13 seconds, at least according to the model used in this research. This difference of 0.13 seconds lowers the capacity from 3600 to 3172; a 11.9% drop. Although the 2030 scenario also has 3% SAE-4 equipped vehicles these cannot influence the average time headway positively. Due to this small share in the vehicle mix no SAE-4 is followed by another of its kind. Because of this the time headway of these vehicles stays at 1.1 seconds which is 0.1 higher than the average of human drivers in the model.

Table 8.10: Results from the base and 2030 scenarios.

Scenario	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of uncomfortabl e decelerations	Occurrenc e of stop-and-go waves?
Base	96.9 km/h	15.7%	11.5%	79.0%	0.98%	Yes
2030	87.0 km/h	18.3%	10.8%	66.3%	0.85%	Similar to base model

Besides a capacity drop a few other indicators change as well. Table 8.10 shows in what way these values differ from the base scenario. In this scenario a few things happen. Striking is that by introducing the sizeable share of SAE-2 vehicles the time spent in stagnant traffic increases while the time spent in standstill actually decreases. Apparently is this SAE-2 share enough to create stop-and-waves where less vehicles have to break to a total stagnant state. Due to the higher time headway SAE-2 vehicles brake earlier. In many cases vehicles do not have to brake harder than the uncomfortable threshold of $3m/s^2$. This result of less uncomfortable decelerations is shown in the table.

Due to the increased time in slower traffic, less time is spent at higher speeds. There is a sizeable difference between the time spent near maximum speed and average speed between the base and 2030 scenario. Figure 8.9 shows what percentage of the 4000 time steps is spent in certain speeds. Here is seen that vehicles in the base scenario are able to drive often near the maximum speed which greatly enhances the average speed. Drivers in the 2030 scenario will drive slower but encounter less situations where they have to brake heavily. This can indicate that the 2030 is somewhat safer, but more research would be needed to prove this. Still a similar amount of stop-and-go waves is formed. By the merging from the on-ramp to the main lane enough disruptive maneuverers are made which together trigger a traffic wave. In this scenario not enough space is present for all vehicles to merge without hampering the following vehicles.

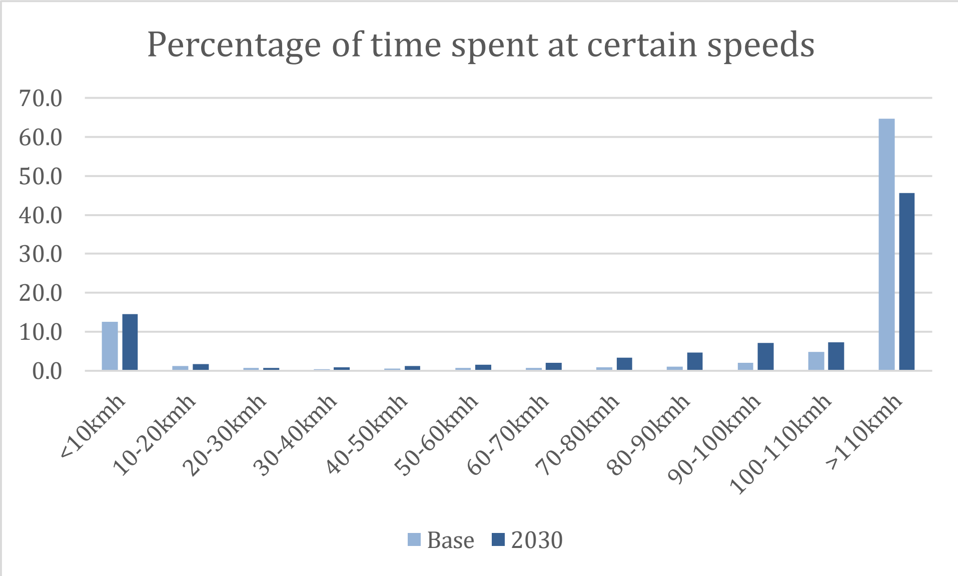

Figure 8.9: Percentage of time spent at certain speeds

When comparing figures of the base scenario and the 2030 scenario a similar pattern is visible. Figure 8.10 shows that a big wave is formed which keeps growing until the last time step. Behind this smaller waves are formed. Between these waves vehicles can accelerate, but within seconds a new wave makes the drivers slow down. Due to the higher acceleration rates of SAE-2 vehicles stop-and-go waves are more quickly 'escaped'. If the acceleration at the end of a wave is higher than the deceleration when approaching the wave, the wave will dissolve. In the 2030 this is not the case yet, but the difference between the acceleration and deceleration is likely smaller than in the base model. Because of this the first big wave is spreading more slowly in the 2030 scenario. Another striking difference between the figures is the pace of the wave itself. Waves in the 2030 scenario are more diagonal which indicate that the waves are moving faster than in the scenario with 100% human drivers. Calculations show that the waves move with 9 km/h. This is 2 km/h faster than the base model, but not yet the 15 km/h often observed in real-life.

It is clear that the vehicle mix corresponding with the 2030 scenario has positive and negative impact on traffic flow. Less situations are created where vehicles brake uncomfortable. Besides is less time spent in total standstill. Meanwhile capacity drops with 11.9%, the average speed decreases with 9 km/h and stop-and-go waves still exist. Interesting is to see if the 2035 scenario creates more positive effects. The next segment shows these results.

The colours in the figures correspond with the three vehicle groups. Human-driven vehicles are depicted in **black**, SAE-2 equipped vehicles in **red** and SAE-4 equipped vehicles in **blue**.

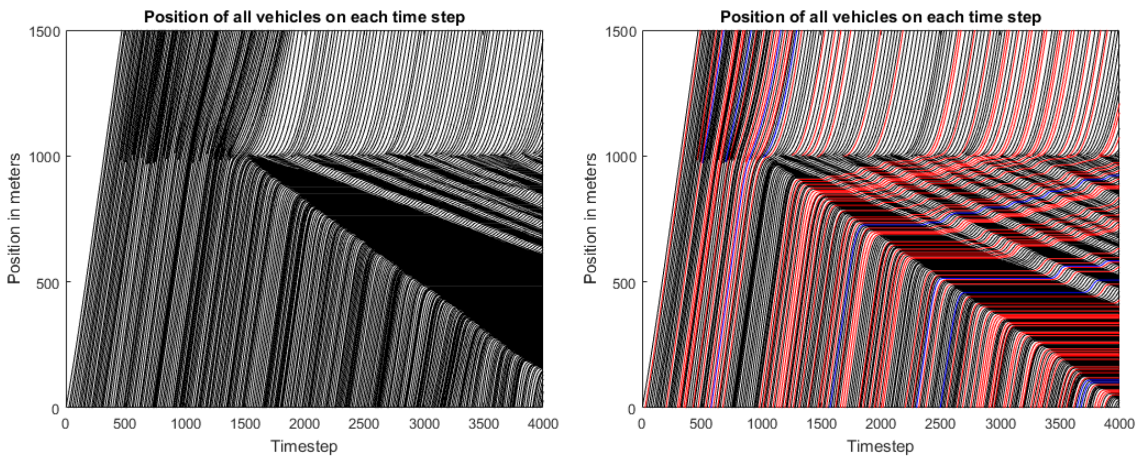

Figure 8.10: Comparing the time-position figures of the base and 2030 scenario

8.4.2 2035 scenario

The 2035 scenario corresponds with a vehicle mix with 40% SAE-2 and 6% SAE-4 equipped vehicles. The remaining 54% is driven by humans.

In the predictions of Calvert et al. (2017) the SAE-2 vehicles would have some kind of connectivity. In the model this wasn't implemented because to time and coding limitations. Besides it was hard to determine in what way this connectivity for SAE-2 vehicles would look like.

With a 40% share of these unconnected vehicles with a higher time headway than human drivers, the capacity drops. The average headway raises to 1.23 seconds, which is 0.23 seconds longer than the base model. Moreover, this is 0.10 seconds longer when comparing with the 2030 scenario. In the 2035 scenario the capacity will be 2923 vehicles per hour. This is a drop of 18.8%. Again, this is mainly due to the higher time headway of the SAE-2 vehicles. The share of SAE-4 vehicles is too small to create a positive outcome; only one instance is found where the headway can be lowered to 0.6 seconds. The rest of the SAE-4 vehicles were driving alone and so the time headway stayed 1.1 seconds.

Table 8.11: Results from the base, 2030 and 2035 scenarios.

Scenario	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of uncomfortable decelerations	Occurrence of stop-and-go waves?
Base	96.9 km/h	15.7%	11.5%	79.0%	0.98%	Yes
2030	87.0 km/h	18.3%	10.8%	66.3%	0.85%	Similar to base model
2035	85.5 km/h	17.8%	7.6%	63.1%	0.63%	Similar, yet more small waves

The other results of this scenario are shown in Table 8.11. The 2030 scenario was added to this table to show that the 2035 scenario is its logical successor. The patterns found in the 2030 scenario are also found in the 2035 scenario results. 5 years later and the traffic flow has not improved but is degraded. Besides that, the maximum capacity is dropped, the average speed lowered with 11 km/h and the time spent at near maximum speed has declined.

It is interesting to see that the percentage of time spent in standstill is 66% the size in this scenario when comparing with the base scenario. Also, in this scenario more time is spent in the slow driving part and not as much standing still, just like in the 2030 scenario.

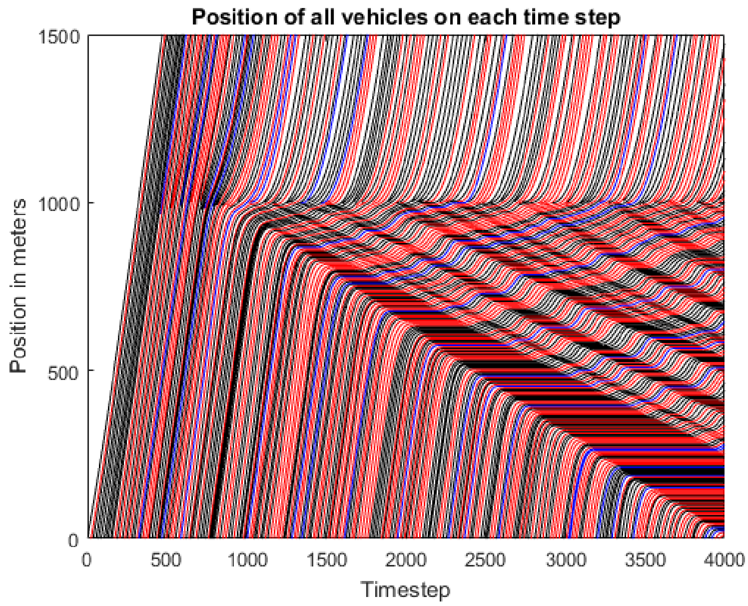

Figure 8.11: Time versus position figure of 2035 scenario

Also, the time spent in uncomfortable decelerations has decreased with a third. This again indicates less disruptive maneuverers. But if looked is at Figure 8.11 it is clear that in this scenario stop-and-go waves still occur. In this scenario the first wave is smaller than in the 2030 scenario. Therefore, more room is present for smaller waves to form behind this bigger first wave. These waves travel with a similar pace of the ones found in the 2030 scenario; namely with 9 km/h.

These waves form because there still isn't enough space for merging. Due to the higher time headway some drivers are cut off by incoming traffic. The model is set up that vehicles have to do a mandatory lane change if they couldn't merge in 6 seconds. These 6 seconds correspond with 200 meters when driving 120 km/h. In scenario's where vehicles with a lot of different headways are driving, merging is often difficult. This is why these mandatory merges are executed. As these do not check for possible space, these mandatory merges are often disruptive. Figure 8.12 shows a close-up of a situation happening in the 2035 scenario.

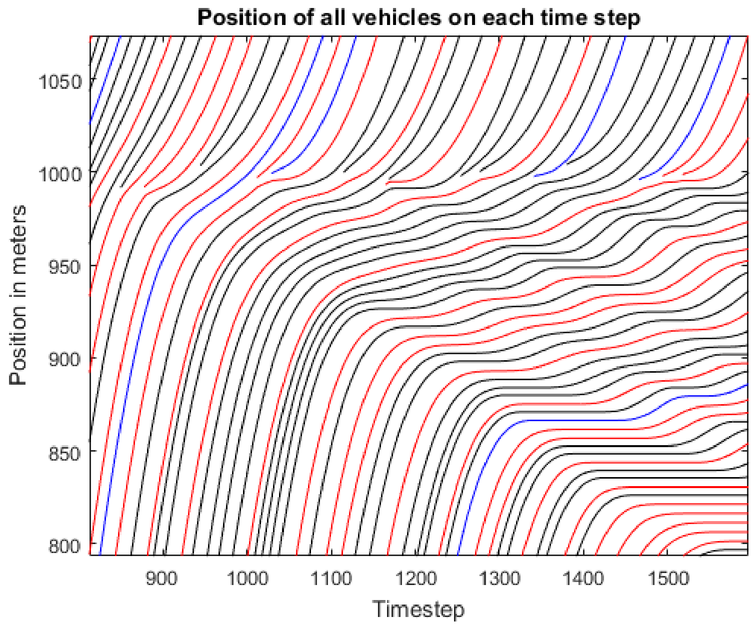

Figure 8.12: Close-up of the formation of stop-and-go waves in the 2035 scenario

In this figure it is visible that with the merge settings merges come often directly right after another. In these actions waves are formed because the vehicle on the main road is cut off. A clear example is the two vehicles merging just before time step 1200. These two vehicles cut off a human driver who has to brake hard which results in a standstill. Due to the limited space, its following vehicles also come to a stop; a stop-and-wave is formed. When this figure is studied multiple instances where stop-and-go waves are formed can be found.

When the 2035 scenario is compared with the 2030 and base scenario the capacity is relatively low. This is due the greater time headway average. The increase in the headway is also responsible for a lower average speed. But, a higher time headway doesn't only have negative effects. Due to the greater distances between vehicles, less uncomfortable and thus dangerous merges been done. As SAE-2 vehicles, which make up a great part of this vehicle mix, are designed for comfort and safety this result is as expected.

8.4.3 100% SAE-2

This scenario corresponds with 100% vehicles equipped with SAE-2. No SAE-0 equipped, as no real self-driving vehicles are part of this scenario. Chapter 8.3 already showed that the capacity of this vehicle was the lowest in the research. Compared with the other capacities 2.400 vehicles per hour is not much, albeit that this would be similar to high observed capacity values in the Netherlands.

Table 8.12: Results from the base and 100% SAE-2 scenarios

Scenario	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of uncomfortable decelerations	Occurrence of stop-and-go waves?
Base	96.9 km/h	15.7%	11.5%	79.0%	0.98%	Yes
100% SAE-2	82.0 km/h	13.9%	0.01%	47.6%	0.05%	Not completely, slowdowns instead of waves

A few results from the SAE-2 stand out when compared with the values corresponding with the base model. What is really striking is the time spent in total standstill. Only 0.01% of the time is spent driving 0 km/h. This while 13.9% of the time is spent in stagnant traffic. As we can see in Figure 8.13 do all vehicles in this scenario slow down when encountering waves formed at the on-ramp location.

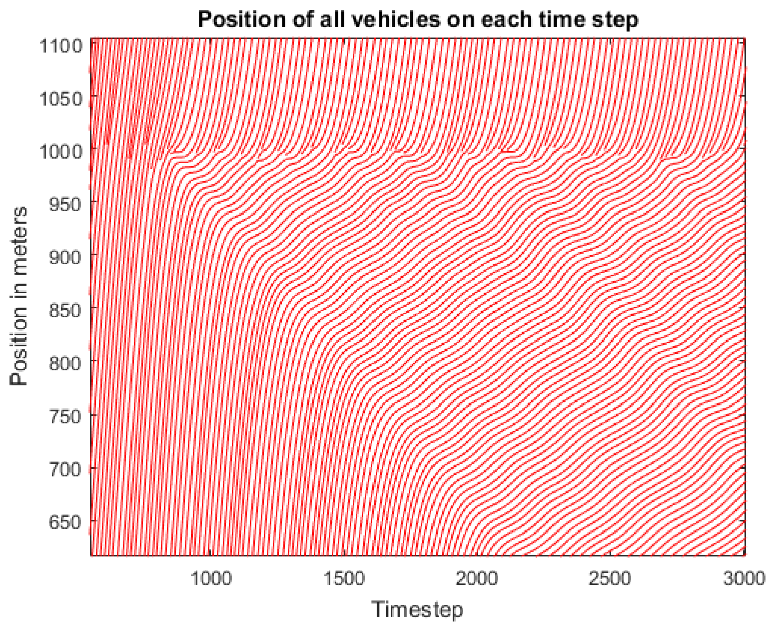

Figure 8.13: Time versus position figure of 100% SAE-2 scenario

Due to the greater distances between vehicles not a lot of disruptive merges are performed and when these are performed the SAE-2 vehicles have enough space to brake comfortably. The larger time headway creates a more comfortable and safer highway. This is indicated by the low percentage of uncomfortable decelerations of 0.05%. These characteristics of a vehicle mix of 100% SAE-2 vehicles create different traffic waves than the stop-and-go waves observed in the previous scenarios. Some disruptive actions are felt minutes and hundreds of meters further, but no total standstill is encountered as driver. The greater time headway creates slowdowns and no classic stop-and-go waves.

When looked closely at Figure 8.13 it is visible that some waves in this scenario are able to fade away. Slowly but as time goes by some of the slowdowns are less heavy than when they are formed. Small differences between speed are in most cases still observable at the end of the simulation.

Another remarkable result of this vehicle mix is the velocity of the vehicles affected by the slowdowns. The merging vehicles clearly still have effect on the speed before the on-ramp. The time by vehicles spent driving at near maximum speed is considerably lower than in the base model. The percentage is reduced to 47.6% due to the time spent between the first wave and the merging location.

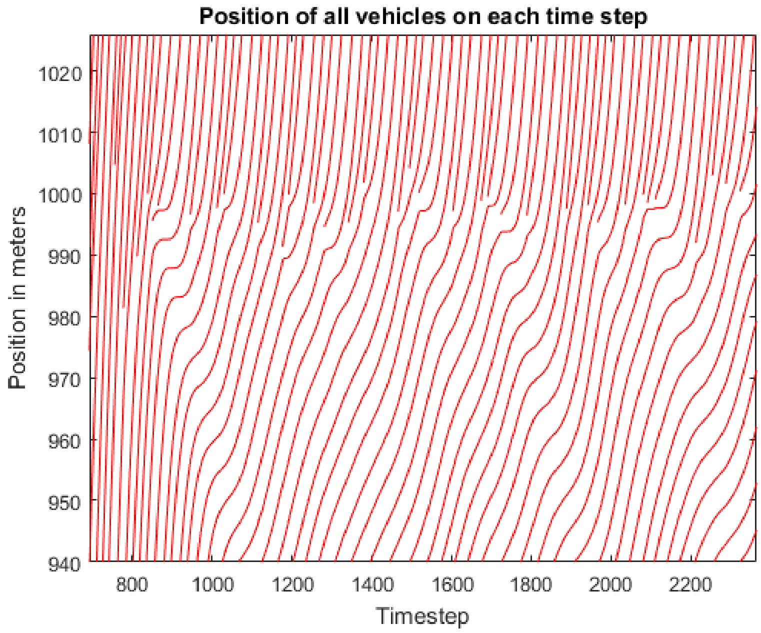

Figure 8.14: Close-up of the formation of stop-and-go waves in the 100% SAE-2 scenario

The close-up in Figure 8.14 shows that vehicles in this scenario are still competing for space. Merging vehicles sometimes interfere with a following vehicle on the main lane. Many lane changes go well and do not or barely disturb the traffic flow while other merges can be considered as too close. In this case the following vehicles time headway is greater or close to the present space. If the preferred time headway is much larger than the actual present time headway hard braking actions are necessary. In Figure 8.14 multiple instances can be seen where this is happening. In most cases are multiple merges responsible for the forming of the waves.

This segment showed us that a scenario with 100% SAE-2 equipped vehicles has positive effects for safety and comfort. The results indicate that the time spent decelerating uncomfortable has been reduced with the 100% SAE-2 vehicles. Besides that, the time spent in total standstill is diminished to 0.01%. On the other hand, the effects felt in traffic flow are mainly negative. In the model the average speed drops to 82 km/h and between the first wave and the merging location vehicles spent a lot of time in stagnant traffic. Previous segments also showed that with the chosen parameters the capacity is likely to drop with 33.3%. If besides safety and comfort gains traffic flow improvements are desired SAE-4 equipped vehicles will probably be the answer. The next chapter show the effects on traffic flow of a vehicle mix of 100% self-driving vehicles.

8.4.4 100% SAE-4

This scenario corresponds with a future where all traffic is automated. All vehicles would be self-driving and would be able to drive without any human intervention, at least on the highway this would be possible. A vehicle mix with 100% SAE-4 equipped vehicles means that every vehicle would be able to drive 0.6 seconds behind a leading SAE-4 vehicle. As chapter 8.3 already showed does these 0.6 seconds correspond with a maximum capacity of 6000 vehicles per hour per lane.

Table 8.13: Results from the base and 100% SAE-2 scenarios

Scenario	Average speed	Percentage of time in stagnant traffic (<25 km/h)	Percentage of time in standstill	Percentage of time near maximum speed (>90 km/h)	Percentage of uncomfortable decelerations	Occurrence of stop-and-go waves?
Base	96.9 km/h	15.7%	11.5%	79.0%	0.98%	Yes
100% SAE-4	119.6 km/h	0.00%	0.00%	99.8%	0.00%	No

Table 8.13 shows the results from the model when run with 100% SAE-4 vehicles in the mix. Every indicator shows that no stop-and-go waves are formed in this scenario. Vehicles are able to drive close to maximum speed more than 99.8% of the time. This is why the average speed is also close to 120 km/h.

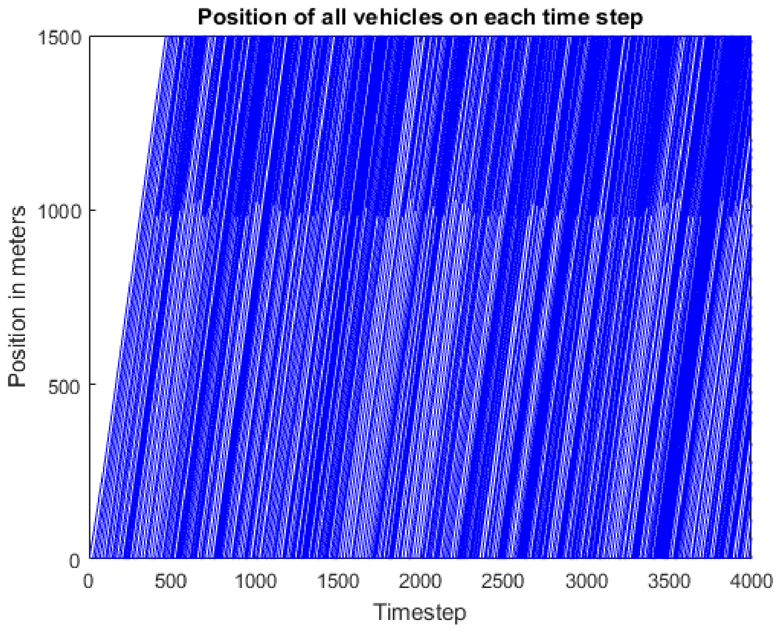

Figure 8.15: Time versus position figure of 100% SAE-4 scenario

Figure 8.15 shows what happens at the on-ramp in the scenario. Merging vehicles have no trouble with finding the possible space between two vehicles on the main lane. This is mainly due the fact that maximum capacity is not reached yet. In the model vehicles start 40 meters from each other. This corresponds with a crowdedness of 3000 vehicles per hour. Thereby does the on-ramp provide a vehicle every 5 seconds, albeit with a bit of randomness. If every 5 seconds a vehicle is driving by this means that the crowdedness of the on-ramp is 720 vehicles per hour. Thus, after the traffic of the on-ramp is merged on the main lane 3720 vehicles are passing per hour. If traffic can't handle this amount, like in the base scenario, traffic waves will form. But if the maximum capacity is higher than this 3720 vehicles, like in the 100% SAE-4 scenario traffic can flow freely. With a maximum of 6000 vehicles per hour enough space per vehicle is present to drive freely and allow for the merge action. That enough space is present is made visible in Figure 8.16

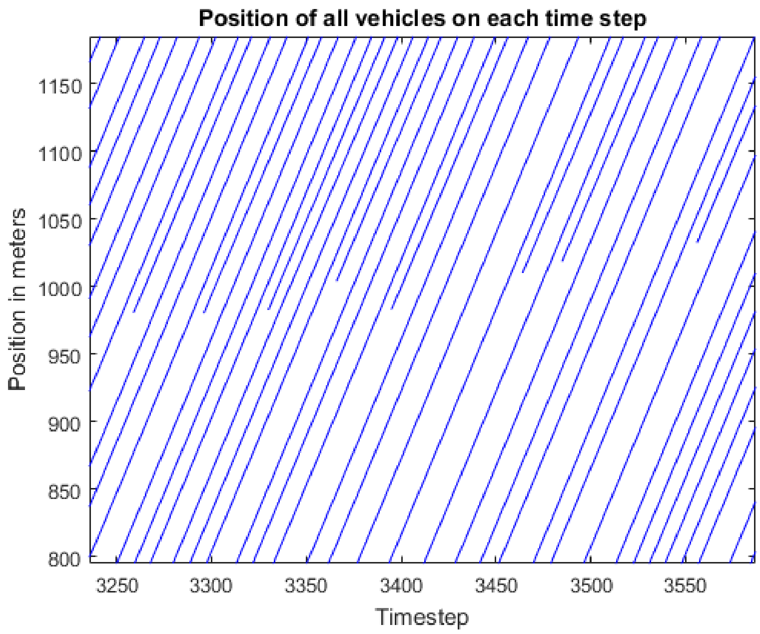

Figure 8.16: Close-up of the formation of stop-and-go waves in the 100% SAE-2 scenario

The figure shows that following vehicles do not have to react on the new vehicles coming in. These vehicles come in at a greater distance than the distance corresponding to the 0.6 seconds of the time headway preferred by the SAE-4 vehicles. Therefore, all vehicles can keep driving at maximum speed and traffic flow is not disturbed.

With a high capacity of 6000 vehicles per hour, an average speed of 119.6 km/h and no stop-and-go waves is the 100% SAE-4 the most positive scenario of all but it is probably the most far away as well. Predictions of whenever this 100% is achieved range from 30-70 years and the possibility exists that it will never happen. Still are the results of this scenario hopeful. This is because this scenario proves that introducing connectivity pays off. Without it maximum capacity tends to drop instead of increase and stop-and-go waves are still present.

8.5 The disappearance of stop-and-go waves

As this research is aimed at the question: "*To what extent can vehicles equipped with SAE-level 2 or SAE-level 4 influence or prevent stop-and-go waves formed at bottlenecks?*", it is interesting to see at what point the traffic waves disperse. When we take a look to the different vehicle mixes used in the previous chapters the answer to this question lies somewhere between 60% and 80% SAE-4 vehicles with the remaining vehicles being controlled by human drivers. Further studying vehicle mixes between these values showed that at 77% the first highway is modelled without any slowdown. Figure 8.17 shows the difference between this 77% SAE-4 vehicle mix and the 76% variant. Left the 76% variant, here a slowdown is visible around the last time steps. The right graph in the figure has 77% SAE-4 vehicles. In this simulation with 4000 time steps no slowdowns are found.

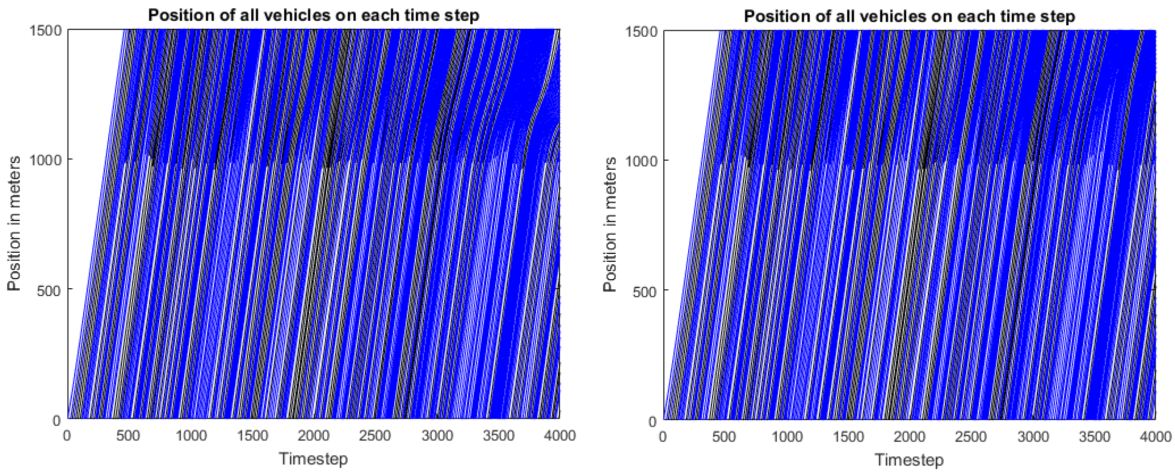

Figure 8.17: Comparison of vehicle mixes containing 76% (left) and 77% (right) SAE-4 vehicles

9. Discussion and Conclusion

The results chapter showed several outcomes about the effects of SAE-2 and SAE-4 vehicles on capacity and stop-and-go wave forming. The behaviours of these vehicle groups differ from human driven vehicles and each other. One effect of these differences is the increase or decrease of the maximum capacity. Essential in the model is the role of the time headway of the vehicles. These are directly linked to the capacity. Table 9.1 shows the theoretical capacity values of 100% penetration of each vehicle group and the two other scenarios set up in the Methods section (7.9).

Table 9.1: Time headway and capacity values of the five scenario's.

Scenario	Time headway values	Average time headway	Capacity	Percentages of difference with 100% SAE-0
Base	0.5-1.5 s	1.0 s	3600 vehicles/hour	0%
2030	-	1.13 s	3172 vehicles/hour	-11.9%
2035	-	1.23 s	2923 vehicles/hour	-18.8%
100% SAE-2	1.2-1.8 s	1.5 s	2400 vehicles/hour	-33.3%
100% SAE-4	0.6 s	0.6 s	6000 vehicles/hour	+66.7%

Due to the greater time gaps assigned to the SAE-2 group maximum capacity values drop when the share of this groups grows. The 2030 and 2035 scenarios contain 25% and 40% SAE-2 equipped vehicles respectively and only low shares of complete self-driving vehicles. Because of this capacity is lower than in the base scenario which represents the current day vehicle mix.
This decrease of capacity is not a result often seen in the used articles. Shladover et al. (2012) found a 1-4% increase when replacing the human-driven cars with 'uncooperative autonomous cars' while Chang and Lai (1997) measured a 33% increase. Calvert et al. (2017) showed a small decrease when switching to LCA and ACC equipped vehicles so it is not unusual to see this happening in articles. It should be noted that the decrease 33.3% in this research is quite high. This difference is due to the chosen time headways which creates a great discrepancy between human-driven and SAE-2 vehicles. These sets of time gaps are not often used in other research. Besides are these capacities theoretical and not operational values. Humans tend to drive in platoons where the chosen time headways are observed. Outside these platoons the time gaps are greater. As the 3600, and other capacities in this research, are based on the chosen time headways a discrepancy between theory and reality is present.

In contrast to the LCA and ACC equipped SAE-2 vehicles do the CACC equipped SAE-4 vehicles have a positive effect on capacity. When following non-SAE-4 vehicles the time headway of these vehicles is 1.1 seconds, but when another SAE-4 vehicle is followed this is decreased to 0.6 seconds. If all vehicles are self-driving the capacity rises with 66.7% to 6000 vehicles per hour. As the penetration rate of this group grows, the amount of vehicles platooning rises strongly. When 18% or a higher percentage of the vehicles is equipped with SAE-4 the average headway will decrease and maximum capacity enhance. Thus, the positive effects are felt.
The 66.7% increase is a result which falls between the capacity values found in literature. The consulted articles tend to have extremely divergent estimates. These estimates range from a 20-50% (Ni et al., 2010) to 270% increase (Tientrakool et al., 2011). Steven Shladover, a leading figure in the discipline, calculated an increase of 80% (Shladover, 2011) and 97% (Shladover et al., 2012) when CACC is introduced. The outcomes in this research come close to these estimates. Again this is a result of the chosen parameters. A relatively high capacity value for human drivers is the cause for a relative low increase of capacity. If the capacity for human-drivers would be around the observed values of 2400 vehicles per hour the increase when SAE-4 vehicles are introduced would be 150% which is high but not unimageable.

This research showed that introducing SAE-4 has more advantages in traffic flow than only an increase in maximum capacity. At high penetrations (>77%) stop-and-go waves will disappear. This percentage will probably drop even more if the inflow of traffic is not as high as it is in the model. The traffic waves disappear because no disruptive merging actions are made at the on-ramp location. The low time headway of the CACC-equipped vehicles ensures that in any situation non-disrupting lane changes can be executed. In the 100% SAE-4 scenario the average speed was virtually equal to the maximum of 120 km/h. Besides no uncomfortable decelerations were measured, so traffic could drive through perfectly.
In the SAE-2, 2030 and 2035 scenarios this wasn't the case. Due to the predominantly presence of SAE-2 vehicles in these scenarios stop-and-go waves kept forming. Instead of classic stop-and-go waves slowdown waves propagated upstream. Also striking was that the amount of uncomfortable decelerations decreased significantly. This indicates that traffic became more comfortable and safer in these scenarios. On the other hand, the average speed did decrease as well. Concluded can be that increased safety but decreased traffic flow makes these scenarios a mixed bag.
This image of a mixed bag is confirmed in earlier research. Because of the fact that SAE-2 vehicles are equipped with ACC perturbations still will be amplified upstream (Ploeg et al., 2011). ACC-equipped vehicles need too much space and cannot react on braking actions taking place many vehicles ahead. In the model this is represented with the higher time headway. A scenario with high shares of SAE-2 and/or human-drivers can't ensure traffic flow stability at high capacities. Disturbances still tend to form traffic waves which can propagate with 7-9 km/h. Due to unclear reasons this is slower than the examples seen in the article by Laval and Leclercq (2010). A 100% SAE-4 penetration provides traffic flow and string stability and so no traffic waves are formed.

The outcomes of capacity and stop-and-go wave forming are all affected by the chosen parameters in the model. Unorthodox about these parameters is the low values of time headway of human-drivers. Earlier research showed that values between 0.5 and 1.5 seconds were the most often observed and therefore these values were used in the model. Hereby must be taken in account that these are desired time gaps and not the average distance measured in observations. Humans tend to drive in platoons on the highway. Within these platoons the 0.5-1.5 time gaps are present but this doesn't mean that the average time gap is 1 second. Because of limitations in coding and choices concerning the complexity of the model these platoons weren't included in the model. This resulted in a high maximum capacity of 3600 vehicles per hour for human drivers which heavily affected the outcomes of this research. Capacity values for SAE-2 vehicles became relatively negative while the effects of SAE-4 equipped vehicles kept subdued.
The fact that the chosen time gap value has a lot of impact is good to keep in mind in the conclusion. Between the three vehicle groups only two parameters are changed: the desired time gap and the acceleration rate. The latter has limited influence of the model, as it is mainly impacting the ability to drive away quickly from stop-and-go waves. This impacts the formation and propagation of the traffic wave, yet is impact of the acceleration parameter limited. Because of the great impact of the time headway parameter the model is simple to use and adjust. The crux of modelling is to create a model which can simulate reality but keep it simple as well. In this sense the model made for the thesis may have succeeded, but one can question if it isn't too simple.
The reason why the model was kept simple was a combination between two factors. As this is the first instance were the modelling environment MATLAB was used by me, a lot had to be learned and explored before simple elements could be used. If more time was on hand more complex features could have been added. Examples of this are the addition of platoons, a politeness factor or a tactical sense to the different vehicle groups. These would have made the model more realistic, yet more complex as well. For future research these elements would be a fine addition, though must kept in mind that the model shouldn't become too complex.

A simple model also has positive effects. The model is easy to understand for new users. This makes the subject and traffic engineering more open for layman. Besides, researchers who are new to modelling can use this model as a base for their own research. In that case the thesis itself

can be used as a base document as well. Due to the fact that I am an outsider of the discipline myself the rapport is fairly entry level. This should help understand the elements which are essential when studying self-driving vehicles and stop-and-go waves.
Something which can interest to layman as well is the 2030 and 2035 scenarios. These years, which are quite close, can spark interest. Mainly if shown that the then common SAE-2 vehicles will bring negative effects to traffic flow, people can become more realistic about assisted and self-driving cars. As the dawn of 2030 is in about a decade, this research can tell everyone about the possible futures and how these SAE-2 and SAE-4 vehicles can influence their daily lives.

As the 2030 and 2035 scenarios are coming more research seems necessary about the lower-level SAE vehicles. Future research should clarify which headways will actually be used by the humans directing the SAE-2 vehicle. In this way the time headway can be more specified. Besides would the introduction of some form of connectivity in SAE-2 vehicles enhance its usability. Interesting would be to see if it is possible to implement this in a way. Maybe this research direction isn't as spectacular as research to the more appealing self-driving cars, but it seems necessary to know how the short-term future will look like. Calvert et al. (2017) wrote about the low-level SAE vehicles, but more research is needed to explore the aspects to these vehicles and their relation with regular human-driven vehicles. Are the positive effects outweighing the negative effects for traffic flow and in what way can these negative traffic flow effects be mitigated are questions still unanswered.
It will also be interesting to see how these vehicles will actually drive in highway traffic. Real-life tests on the open road will be a great source of data which will sharpen our vision of the near future. Here can be observed if models created to research SAE-1/2 were right and what the real-life effects of these vehicles are. With this information the calculations done to come to the capacity values can be enhanced as well. Now theoretical capacities in this research are significant different than the operational ones observed on the real highway. For future research a sharp look must be given to these capacity values. Which factors drop the theoretical capacity to the operational one and are these factors present when SAE-2 and SAE-4 are added to the vehicle mix? To research this properly a more complex model with platoons is necessary.

The future studies and research like this thesis are essential for institutions responsible for the safety and traffic flow on the highways. It must be questioned if low-level vehicles are desired at all and if that is the case, in what form. A potential decrease of 33.3% on traffic flow can slow or even shut down whole highway systems. A system as busy as the one of the Netherlands knows big differences during rush hour and normal commute (KiM, 2017). High penetrations of ACC and LCA-equipped vehicles can bring unexpected and great problems.
This is why the preference exists for connected vehicles like the SAE-4 vehicles. Cooperation between vehicles is essential for positive outcomes. For this to happen, governments and car manufacturers should make agreements about a system in which every vehicle can share information. Otherwise the potential of the SAE-4 technology aren't expected to be reached.
The fact that vehicles are replaced every 15 years (Litman, 2017) will mean that SAE-2 vehicles sold in 2030 will still be around in 2045. This could slow down progression towards a system where all vehicles are self-driving. The advice is to obligate to make SAE-2 vehicles able to be upgraded towards higher levels. In this way these vehicles can be changed from SAE-2 to SAE-4 overnight. In this way one software update can improve traffic flow and even safety indefinitely.

The central question in this research is: ***To what extent can vehicles equipped with SAE-level 2 or SAE-level 4 influence or prevent stop-and-go waves formed at bottlenecks?***

SAE-4 vehicles are able to prevent stop-and-go waves from happening, but SAE-2 isn't the right fit to do this. Clear is that there is a big difference in what SAE-2 and SAE-4 can do for traffic flow. SAE-4 vehicles are able to drive close to each other which increases theoretical capacity with 66.7%. Due to this more space is present to merge into which prevents disruptive lane changes and so the formation of stop-and-go waves. Besides, these vehicles are able to accelerate faster

than human-drivers. This feature also helps preventing traffic waves forming as these are a product of a higher deceleration than acceleration at the end and beginning of the slowdown respectively.
This feature is also found in the SAE-2 vehicle group, but not enough to prevent the formation of the traffic waves. With 100% ACC and LCA-equipped vehicles theoretical capacity drops with 33.3% and mergers are forced to hamper other vehicles when changing lanes at the on-ramp. These vehicles do succeed in increasing comfort and safety when compared with human drivers. It can be concluded that vehicle connectivity is key to achieve traffic flow improvements and there must be strived to introduce self-driving cars instead of vehicles with assistances to prevent stop-and go waves forming.

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Appendix 1: MATLAB-model

Core of the model:

```
function[veh]=Kik20022019()

%% Simulatie setup
tstep = 0.1;
ttot = 4000;
xtot = 5000;
xmerge = [1000:1200]; %positie in voegstrook
numvehMerge = 300;
global numveh;
numveh = 500; %aantal voertuigen
global vi;
mergeFreq = 50; %average number of time-steps between merges
t_firstMerge = 400; %t-step of first merging vehicle
ds_default = 20; %default distance between vehicles
viM = 1; %vehicle merging counter
minGapBack = 0.6; %s
maxMergeDur = 60; %maximum tijd dat een vtg probeert in te voegen in time-steps
T_sae4 = 0.6;

sae_distr = [0.6 0.8 1.0]; %cumulatieve verdeling van de SAE-level = 0; 2; 4
sae_level = [0 2 4];
rng(1); iAV_rnd = rand(1,numveh); %random numbers for SAE level assignment
rng(4); iAVmerge_rnd = rand(1,numvehMerge); %random numbers for SAE level
assignment; invoegers
rng(2); x_rnd = rand(1,numveh); %random numbers for initial space headway deviation
rng(5); T_rnd = rand(1,numveh); %random numbers for difference in T for ACC (SAE2)
rng(3); tMerge_rnd = rand(1,numvehMerge); %random numbers for time-steps of veh
merge
tMerge = round(t_firstMerge+(0:numvehMerge-1).*mergeFreq +  90.*(tMerge_rnd-0.5) );
%time-steps in which a merge takes place
tMergeDef = tMerge; %static tMerge value

%% Voertuigen definieren
%blabla
% amax, v0, s0, T, bcomf, alfa, bmax
for vi=1:numveh
   veh(vi).amax = 2;
   veh(vi).v0 = 120/3.6;
   veh(vi).s0 = 5;
   veh(vi).T = 1.44;
   veh(vi).bcomf = 3;
   veh(vi).alfa = 4;
   veh(vi).bmax = -8;
   veh(vi).a(1) = 0;
   veh(vi).v(1) = 100/3.6;
   veh(vi).tsim(1) = 1;

   sae_idx = find(iAV_rnd(vi)<=sae_distr,1,'first'); %index voor SAE level
   veh(vi).sae = sae_level(sae_idx); %assign SAE level
   if vi==1
       veh(vi).x(1) = 0;
   else
       %veh(vi).x(1) = veh(vi-1).x(1)-ds_default; %define vehicles starting
location WITHOUT randomness
       veh(vi).x(1) = veh(vi-1).x(1)-ds_default+50*(x_rnd(vi)-0.5); %define
vehicles starting location WITH randomness
   end

   if veh(vi).sae==0
       veh(vi).T = 1.0 +1.0*(T_rnd(vi)-0.5);%range 0.5-1.5
       veh(vi).amax = 1.25;
   elseif veh(vi).sae==2 %Assigning SAE-specific characteristcs
       veh(vi).T = 1.5 +0.6*(T_rnd(vi)-0.5);  %range 1.2-1.8
       %veh(vi).amax = 2;
```

```
    elseif veh(vi).sae==4
        veh(vi).T = 1.1;
        %veh(vi).amax = 2;
    end

    veh(vi).xtemp = veh(vi).x(1); %current x

end

%       for vi=1:numveh
%           newveh.amax = 2;
%           newveh.v0 = 35;
%           newveh.s0 = 5;
%           newveh.T = 1;
%           newveh.bcomf = 3;
%           newveh.alfa = 4;
%           newveh.bmax = -8;
%           newveh.a(1) = 0;
%           newveh.v(1) = 100/3.6;
%
%       end

%% Simulatie

for t=2:ttot %tijd-lus

    %Vehicle merge
    if ismember(t,tMerge)
        locMerge = xmerge(1); %x location of merge
        seqMerge = find([veh.xtemp]>locMerge,1,'last');  %vehicle sequence location
of merge
        vstart = veh(seqMerge).v(t-1); %invoegsnelheid obv naastliggende voertuig
        newveh = mergeVeh(t,viM,iAVmerge_rnd,sae_distr,sae_level,vstart); %get new
vehicles characteristcs
        if (newveh.sae==4)&&(veh(seqMerge).sae==4) %check for SAE4 cooperation ->
lower T_value
            T_merge = T_sae4;
        else
            T_merge = newveh.T;
        end
        mergeLocFront = veh(seqMerge).xtemp-T_merge*newveh.v(t-1);  %invoeglocatie
obv v*T afstand achter voorligger
        mergeLocBack = veh(seqMerge+1).xtemp+minGapBack*veh(seqMerge+1).v(t-1);
%min invoegruimte achterkant hiaat
        newveh.x(t-1) = max(mergeLocFront,mergeLocBack); %use front gap location,
if this remain within back gap distance
        idxM = find(t==tMerge,1,'first');
        if tMerge(1,idxM+1)<=t %controle van eerstvolgende invoeger
            tMerge(1,idxM+1)=t+1;
            tMergeDef(1,idxM+1)=t+1;
        end
        if
(mergeLocFront<mergeLocBack)&&(tMerge(1,idxM)<tMergeDef(1,idxM)+maxMergeDur) %only
merge if enough space OR if merging time too long
            tMerge(1,idxM) = tMerge(1,idxM)+1; %probeer het t+1 weer
        else
            newveh.xtemp = newveh.x(t-1); %locatie van invoeging temp
            veh = [veh(1:seqMerge) newveh veh(seqMerge+1:end)]; %add vehicle to
road
            viM = viM+1;
            numveh=numveh+1; %increase size of numveh due to an extra vehicle
        end
    end

    %%%%%

    for vi=1:numveh
        if vi==1 %bij geen voorligger
```

```
            ds = 1e10; dv = 0;
        else
            ds = veh(vi-1).x(t-1) - veh(vi).x(t-1);
            dv = veh(vi).v(t-1) - veh(vi-1).v(t-1);
        end

        if  vi>1
    if (veh(vi).sae==4)&&(veh(vi-1).sae==4) %check for SAE4 cooperation -> lower
T_value
            vehIDM = veh(vi);
            vehIDM.T = T_sae4;
     else
            vehIDM = veh(vi);
    end
        else
            vehIDM = veh(vi);
        end

        veh(vi).a(t) = IDMplus(vehIDM, ds, dv);
        veh(vi).v(t) = max(0, veh(vi).v(t-1) + tstep*veh(vi).a(t) );
        veh(vi).x(t) = veh(vi).x(t-1) + max(0, veh(vi).v(t)*tstep +
0.5*veh(vi).a(t)*tstep^2);
        veh(vi).xtemp = veh(vi).x(t); %current x
        veh(vi).tsim(t) = t;

        end

 end
 end
```

IDMplus:

```
function [acc] = IDMplus(vehicle, ds, dv, amax, v0, s0, T, bcomf, alfa, bmax)
% IDMPLUS - car following model according to Schakel & van Arem (2010)
%
% USE It can be called in two ways
% (1) acc = IDMplus(v, ds, dv, amax, v0, s0, T, bcomf, alfa, bmax)
%     in which all inputs are 1xN sized vectors (depicting N vehicles)
%     v: vehicle speedsw, ds: distance gaps, dv: speed differences
%
% (2) acc = IDMplus(vehicle, ds, dv)
%     in which vehicle is a struct with the following fields
%     vehicle.v                 % prevailing speed
%     vehicle.par.amax = 3;     % m/s2 max acc
%     vehicle.par.v0   = 35;    % m/s  des speed
%     vehicle.par.s0   = 5;     % m    stopping dist
%     vehicle.par.T    = 1.2;   % s    min time headway
%     vehicle.par.bcomf= 3;     % m/s2 comfortable acceleration
%     vehicle.par.alfa = 4;     % -    scale parameter (power 1st term)
%     vehicle.par.bmax = -8;    % m/s2 max deceleration
%
%     NB: v0 and T are multiplied by
%     vehicle.ctl.v0fac
%     vehicle.ctl.Tfac
%
%Outputs
%   acc             vehicle acceleration according to IDM+

%%

% parameters per vehicle
if isstruct(vehicle)
    v    = vehicle.v(end);
    amax = vehicle.amax;      % m/s2 max acc
    v0   = vehicle.v0;        % m/s  des speed
    s0   = vehicle.s0;        % m    stopping dist
    T = vehicle.T;            % m    maximum headway
    bcomf= vehicle.bcomf;     % m/s2 comfortable acceleration
```

```
    alfa = vehicle.alfa;      % -     scale parameter (power 1st term)
    bmax = vehicle.bmax;      % m/s2 max deceleration
elseif nargin == 10
    v     = vehicle;
else
    error('IDMplus: incorrect nr of inputs');
end;

% IDM+
ds_star= s0 + max(0, T.*v + v.*dv ./ (2.*sqrt(amax.*bcomf)));
acc = max (amax * ( min( 1-(v./v0).^alfa, 1-(ds_star./ds).^2) ), bmax);
```

Code for merging vehicles:

```
function[veh]=mergeVeh(t,vi,rnd,sae_distr,sae_level,vstart)


   veh.amax = 2;
   veh.v0 = 120/3.6;
   veh.s0 = 5;
   veh.T = 1.44;
   veh.bcomf = 3;
   veh.alfa = 4;
   veh.bmax = -8;
   veh.a(t-1) = 0;
   veh.v(t-1) = vstart; %120/3.6;
   veh.tsim(t-1) = t-1;

   global numveh;
   rng(6); T_rnd2 = rand(1,numveh); %random numbers for difference in T for SAE0
   rng(7); T_rnd3 = rand(1,numveh); %random numbers for difference in T for ACC
(SAE2)

   sae_idx = find(rnd(vi)<=sae_distr,1,'first'); %index voor SAE level
   veh.sae = sae_level(sae_idx); %assign SAE level


   if veh.sae==0

       veh.T = 1.0 +1.0*(T_rnd2(vi)-0.5);

       veh.amax = 1.25;

   elseif veh.sae==2 %Assigning SAE-specific characteristcs

       veh.T = 1.5 +0.6*(T_rnd3(vi)-0.5);  %

       %veh(vi).amax = 2;

   elseif veh.sae==4

       veh.T = 1.1;

       %veh(vi).amax = 2;


   else

   end


end
```

Appendix 2: Design scheme for model and merging

What happens in the model:

1. Simulation setup including highway ‘design’.
    a. t = time, tstep = 0.1, ttot = 1000, xtot= 5000, xmerge = 100-400, numveh = 20
    b. Frequency of merging cars (for example: 1 per 30 * tstep)
    c. One lane, one merging ramp of 300 meters = Dutch standard (xmerge)
2. Define vehicle behaviors (humann, SAE-2, SAE-4)

Parameter	**Human**	**sae2**	**sae4**
amax	3 m/s^2	3 m/s^2	3 m/s^2
v0	120 km/h = 33.3m/s	120 km/h = 33.3m/s	120 km/h = 33.3m/s
s0	5 m	5 m	5 m
Tregular	1.2 s	**1.5 s**	**0.5 s**
TSAE4	1.2 s	**1.0 s**	**0.2 s**
bcomf	3 m/s^2	3 m/s^2	3 m/s^2
bmax	-8 m/s^2	-8 m/s^2	-8 m/s^2
Alfa	4	4	4
p (politeness)	**Rand**	1	1

    a. Built-in a mechanic to create a division of the three groups. (For example: Veh= 0.5 Human-driven, 0.2 SAE-2, 0.3 SAE-4. Together always 1).
3. Cars start driving. First car starts at x=0. Cars start 100 meter after leading vehicle. All have a speed of 100km/h. Spawning of main lane and merge lane vehicles is ‘random’ but based on the rates given in the division.
4. After the first vehicle has passed the first merging cars can come in. A vehicle on the on-ramp has 300 meters to find a suitable spot. This is calculated with gap acceptance theory. Looked will be what the distance is between the potential position of the merging vehicle and the positions of potential leading and following vehicles.
5. In certain situations, stop-and-go waves will form which will travel upstream. This is all dependent on the right balance within the used parameters. The intention is that in standard situation with 100% human-driven cars this occurs. If SAE-4 vehicles are added to the mix the strength of these traffic waves will probably decrease and eventually disappear. Interesting will be what SAE-2 vehicles will do.

6. Vehicles disappear after 5000 meters. The simulation stops when all vehicles (numveh) are past this point and/or the maximum time of ttot is reached. The results are shown in tables, plots and if possible top-down visualisations

1. Simulation setup
tstep = 0.1;
ttot = 1000;
xtot = 5000;
xmerge = [100:400];
numvehmerge = 50;
numveh = 20;

2. Set rates of vehicle groups for division
veh.human = 0.5;
veh.sae2 = 0.3;
veh.sae4 = 0.2;
If veh.human + veh.sae2 + veh.sae4 = 1 go to next step
Else = error message that the sum is not 1

3. Define vehicle behavior
All the same except headways and politeness
=> see table.
Create matrix/struct where this is saved. SAE2/SAE4 have different values in Tregular and TSAE4 (if/else statement). Each group should have a different label for further use.

4. Run vehicle simulation
Calculate a,v,x for all vehicles on main lane with IDM+ for every tstep.
The rates of vehicle groups are used for the rates of spawned vehicles. Randomized values linked to these rates make it stochastic

Repeat * ttot

5. Merging
After a tstep calculate if merging vehicle is in place to merge. This is done with something similar to gap acceptance theory. Calculated is if Tregular or TSAE4 is sufficient for a merge. If to check, else try again next step. Most vehicles are willing to make space for merging vehicle. => politeness factor.

Simulation ends after ttot

6. Visualization
In plots and top down view if possible

To-be-built blocks of code:

1. **A controller to set the rates of the different vehicle groups:**
    a. Three different group names: human, sae2 & sae4. **Input = 0-1**. The sum of the three rates should be 1. If ≠ 1 an error message pops up.
    b. These rates have impact on the spawning of vehicles on the main lane and the merging lane. Work with rand function. For example: human= 0.5, sae2 = 0.3, sae4 = 0.2. Than random values between 0 and 0.5 will spawn human-driven vehicles, 0.5-0.8 and 0.8-1 will spawn sae2 and sae4 vehicles respectively. This can be seen as a **stochastic** element.

2. **Connect behaviors to vehicle groups:**

a. Create lists with parameters per group. Built in a way that parameters can be altered per group. Thus, a **flexible design with three lists. See table above.**
b. **Run IDM+ for all three groups** with the different parameters during the same timestep

3. **Code which controls merging:**
    a. Segment to spawn vehicle belonging to one of the three groups. Vehicles spawn at a set period (for example: Vehnew= 10s = 6 per minute). Same random function as on main road. *Option to only add a certain vehicle of one group. (only sae-4 vehicles while human-driven spawn on main road).*
    b. Give this vehicle time and meters to drive at the same speed as the vehicles on the main road. Check what the average speed is of the cars just in front and on highway-ramp and try to match that speed. So **veh.merging(v) = avg(v) (shighway + (shighway - 100))**
    c. Essence of this segment: split the structure to add vehicles. Based on different conditions per group:
        i. Human-drivers try to fit Tregular (or TSAE4) behind the potential leading vehicle and for the potential following vehicle but are not perfect. Add a margin of error where this Tregular or TSAE4 is lower or higher. Which value should be used for this is hard to define, because it has to be scientific correct. In this way every human-driven car has a different headway which indicates when they can merge. = **stochastic**
        ii. SAE-2 vehicles do not have this error mechanism and want merge perfectly in the middle but need greater distances to keep it safe. It can recognize SAE-4 vehicles. Here less distance is needed.
        iii. SAE-4 needs less Tregular and TSAE than SAE2 to merge. Will always try to merge in the middle of potential leading and following vehicle. No errors are made.
    d. Add vehicles. Merging is instant. Adding merging times would makes matters too complex.

4. **Make space for merging vehicle:**
    a. When space is limited the different vehicle groups can make the decision to make some space by accelerating or decelerating. In this case variable 'a' is based on the distance to the potentially merging vehicle. The willingness to make space can be defined as politeness 'p'. p is multiplied with the rest of the equation which defines a. **a= dsmergeposition * p...**
        i. Human-driven vehicles have per vehicle a big difference in politeness. Using random values from 0-1 on a scale of 0-1 as well can make some drivers willing to make space while others are not. **p=rand => stochastic**
        ii. SAE-2 in vehicles is created for comfort and safety. Giving space for a safer merge reduces the chance on accidents. **p=1**
        iii. SAE-4 is created for safety but a stable and fast flow as well. These vehicles are also willing to give space to potential merging vehicles. **p=1**

- ***Visualization:***
    - *Plot graphs to show the eventual formation and propagation of stop-and-go waves.*
    - *Create a highway environment where the vehicles (points/rectangles) move from left to right. This way it is easier to view what is going well and what problems can be solved to make the model smoother/more realistic.*