The Future of Automated Vehicles

Scenarios for automated vehicles and the consequences for mobility, safety and the environment

Bachelor thesis Anne van der Veen - S2322668 - University of Groningen - 2015

Abstract

In the last decade, automation has entered the realm of vehicles. The automated vehicles that are being developed will have a large impact on the transportation network, which in turn impacts mobility. To prepare for what's to come it is vital to get an understanding of what the future might look like. Because the technology is still in an early stage, it can develop in numerous wildly different directions. This research assesses these different directions by looking at what kind of automated vehicles are likely to occur. These vehicle types are defined using two key factors: the level of automation (full / limited automation) and the kind of mobility the vehicle provides (personal / on-demand / centralized). It does not look at the status quo but only at the future, which is why non-automated vehicles are not within the scope of this research. This results in six categories of automated vehicles. The impact of each automated vehicle on the transportation network and on mobility is assessed using scenarios and the assumption that that vehicle type becomes dominant. Using multiple expert interviews, these scenarios are explored. The result is that the impact of automated vehicles is very dependent on the kind of vehicle, that the impacts are complex and rather difficult to predict and that efficiency and that safety are greatly impacted because of these technological advancements.

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Chapter 1: Introduction

1.1: Introduction

Transport and land use are two factors that codetermine each other (Wegener & Furst, 1999). This relation is described in the land-use transportation feedback cycle, wherein land use influences transportation through activities and transportation, in turn, influences land use through accessibility and mobility. One section of this feedback cycle is the influence the transportation network has on mobility. The characteristics of the transportation network –its quality, density, and other similar factors– directly influences travel behaviour. This behaviour then defines mobility and accessibility.

The current transportation network is divided into multiple modalities. Cars account for the largest modal share in terms of passenger miles. In the US alone, passenger cars accounted for almost 60% of all travelled miles in 2012 (Bureau of Transportation Statistics, 2014). Thus, a large change to the automotive landscape, affects the transportation network. If such a change occurs, this also has an important impact on mobility and accessibility.

In recent years, it has been postulated that self-driving vehicles, also called autonomous vehicles (AV's) will lead to a 'disruptive, revolutionary change' (Mui, 2013) to the transport network. It is a 'disruptive innovation' (Timmer, 2014), it 'has the potential to dramatically change the transportation network' (Fagnant & Kockelman, 2013), 'the implications [are] profoundly disruptive for almost every stakeholder in the automotive ecosystem' and they can 'dramatically reshape not just the competitive landscape but also the way we interact with vehicles and, indeed, the future design of roads and cities' (KPMG & CAR, 2012).

Fundamental and technological changes to the car in the direction of autonomy are expected to yield large safety benefits and energy efficiencies (Peters, 2014). If fully implemented, the technology is expected to save thousands of lives, to make driving much more efficient, to reduce congestion and reduce the amount of cars needed dramatically (Anderson, 2014).

However, in what form it will change the transportation network is unclear. Automated vehicle technology is nowadays still in its infancy. The core technology behind most self-driving vehicles has only been in development since 2007, and it might be decades before the technology is widely adopted. (Morrow III, 2014)

However, there are promising prototypes already driving around. For example, Google's AV fleet has driven over 700,000 miles autonomously (Urmson, 2014). Multiple automotive companies aim to have working technology on the market in the next five to ten years, while technical research institutes like MIT and the TU Delft are also working on their own prototypes.

Even though these different companies and organizations are working on the same subject, they use radically different strategies to automate driving. Because driving a car is an inherently complex task, there are multiple ways of automating it. A company like Tesla or Daimler builds upon existing technologies like lane centering and cruise control to automate highway driving, and uses that to incrementally add more autonomous features (Tesla Motors, 2014) Google, on the other hand, is working on a new vehicle designed from the ground up to drive fully automated all the time, not even needing a steering wheel.

These are just two out of the many possibilities that autonomous technology enables. The technology can have an impact on much more than just cars. After all, sensors and steering control can be placed in all vehicles. Some other implementations of this technology are autonomous taxis, truck platooning, closed-environment shuttle services, airport transportation, automated public transport, autonomous farming and autonomous mining. This is why this thesis will focus on automated *vehicles*, and not just cars.

These different kinds of autonomous vehicles have widely different effects on mobility. For example, whether self-driving technology will be adopted in the form of shared taxis or as privately owned vehicles has influence on the role the vehicle has in the transportation network, which in turn results in different consequences for mobility. The aim of this research is to outline different scenarios of automated vehicle technology and to assess their consequences for mobility.

1.2: Research Focus & Goal

It has become clear over the last years that autonomous technology will end up in vehicles and that its potential effects are important enough to study and prepare for. There are multiple extensive reports about the future of self-driving cars already (KPMG & CAR, 2012; Fagnant & Kockelman, 2013; Anderson, 2014; Timmer, 2014). Each of these reports focuses on and argues for a particular scenario of autonomous technology. They look at the future of automated vehicles and assert that a certain kind of vehicle is likely to succeed, e.g. that the future of automated vehicles lies in cooperative, connected cars (Timmer, 2014). Based on that future, policy recommendations and advice to policy makers are provided. The approach used to the future of autonomous technology is that of predictive forecast scenario's (Borjeson et al, 2006): what will happen, on the condition that the most likely scenario occurs?

Because the technology is still in an early stage with many possible outcomes, it is difficult to predict which particular scenario will become reality. While a predictive approach is understandable, the uncertainty with autonomous technology is so high that it is too early to point to a singular future. On top of that, most current research is from or about the automotive sector. As mentioned before, automation can occur in much more than just the cars we know – it can have an impact on different and new kinds of vehicles, from trucks and trains to pods and people movers.

More useful, then, is an inclusive assessment of the different vehicle scenarios–an explorative approach–instead of delving deep into just one (car) scenario. Instead of looking at what is the most likely scenario, a better question is to see what is possible with automated vehicle technology. This question has been addressed only sparsely in the current literature. An inclusive, explorative set of scenarios is also more useful for policy recommendations. It can help to make more specific investments towards a certain scenario, with the realizations that there are other possibilities. It also allows the focus to shift to a different scenario when desired.

Thus, this research asks two major questions: What scenarios are possible with autonomous vehicles, and what is the impact of these scenarios on the transport configuration and on mobility? The result of this research can be used to prepare for this technology in policy and investments. The main question in this research is as follows:

> *What impact will different scenarios of automated technology have on the transportation configuration and on mobility?*

To get to an answer, this research starts by distinguishing the different scenarios from each other. Once the scenarios are delimited the consequences of those scenarios are explored, first for the transportation system and then for mobility. To summarize, these are the sub-questions:

1. *What are the important, inclusive factors that distinguish automated vehicle scenarios from each other?*
2. *What scenarios result from automated technology?*
3. *What are the transport configurations resulting from these scenarios? How is such a configuration different from the current configuration?*
4. *What are the consequences for mobility when that change in configuration occurs?*

1.3. Thesis Outline

Chapter 2, the Theoretical Framework, will outline the relevant theoretical ideas to the research. It will form the theoretical foundation to the chosen scenarios in the conceptual model. Chapter 3 goes into more detail on the methodology used in this research. The fourth Chapter forms the gist of the research, as it answer the third and fourth sub-questions. It will cover the six scenarios and their consequences and concludes with an oversight of the major findings. Chapter 5 will conclude and reflect on the research.

Chapter 2: Theoretical Framework

2.1. Introduction

In the land use-transportation feedback cycle, activities are seen as the major reason for travel to occur. After someone makes the decision that a trip is necessary, the choice of how the trip is made is mostly decided by two factors: the quality of the modality and the relative attractiveness of that modality compared to all other modalities. (Wegener & Furst, 1999)

Automated vehicle technology is used both in existing modalities (e.g. improving cars and buses) and in new modalities (e.g. robo-taxis). Because of this, it makes more sense to talk about different kind of *vehicles* instead of modalities. The choice of how to get from A to B is then influenced by the quality of the vehicle (is is good enough to use) and the attractiveness (sum of the qualities) of the vehicle relative to others in the transport system.

In simpler terms this means that the choice of vehicle is done based on what's available, and from that selection, the option that is most attractive–with the best qualities–is chosen most of the time. If you want to get to another city but you also want to get some work done, the train might be the best option as it is of good quality and because it is more attractive than a bike or a car for working while travelling.

In this chapter, the qualities of autonomous vehicles will be used to differentiate between uses of autonomous technology. Two qualities distinguish self-driving technology from regular vehicles: the level of automation and the type of vehicle ownership. These will be explained in detail. Then, the term transport configuration is discussed as a way of comparing the attractiveness of self-driving vehicles to all other modalities in the scenarios.

2.2. Automation

Existing reports and literature use multiple terms interchangeably to refer to roughly the same thing: self-driving cars, automated vehicles and autonomous vehicles (AV's). These terms might imply that autonomy is something that a car either has or doesn't have, and that these terms are interchangeable.

However, autonomy and automation are not equivalent. To understand this difference, it is essential to think of automation as a spectrum instead of a binary value. Vehicles have a certain *degree* of automation. This degree is determined by the amount of functions that are automated in the vehicle.

The American National Highway Traffic Safety Administration, the NHTSA, has defined the degrees of automation in levels, ranging from Level 0 to Level 4 automation. This hierarchy is also being used for policy making (Anderson, 2014). It defines five levels of automation:

- **Level 0: No Automation**. The driver is in complete control at all times.
- **Level 1: Function-Specific Automation**. The car assists the driver in doing tasks better or faster than without this automation. The driver is still always in control, but has the option to cede some control to the car. Examples are ABS, ESC and cruise control.
- **Level 2: Combined Function Automation**. To be at this level, at least two primary control functions are automated. This means that the driver doesn't have to steer and doesn't have to control the speed, but might have to regain control quickly. An example would be lane centering in combination with adaptive cruise control.
- **Level 3: Limited Self-Driving Automation**. The driver is allowed to cede control of all safety-critical functions, and is only needed occasionally. The system has to warn and give time to the driver when it hands the controls back. It can handle most of the situations by itself.
- **Level 4: Full Self-Driving Automation**. This vehicle can perform all safety-critical features all the time. It can drive completely on its own and doesn't require a steering wheel. The 'driver' is only needed to input directions. (NHTSA, 2013)

For this thesis, a simplified spectrum is used in this thesis with only those levels that matter for mobility: full automation and limited automation (see figure 1 on the next page). Full automation is the highest level. Limited automation covers all the levels between full and no automation.

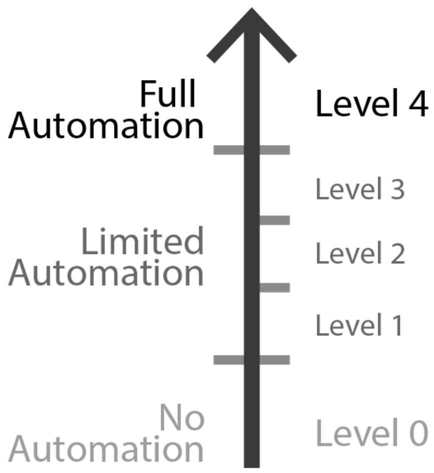

Figure 1, Simplified Levels of Automation

The consequences of self-driving technology for mobility are highly dependent on the degree of automation that is achieved in two distinct ways.

Firstly, having automation or not makes a difference for mobility. Because automation takes over parts of the task of driving, it alleviates the driver from having to pay attention to that function. At a more advanced stage, automated vehicles can take over driving entirely if certain conditions are met. Drivers can focus their attention on a different task, such as working, consuming media or communicating with others safely. Automation also improves the environmental impact and safety of the vehicle.

Secondly, there is an important difference between vehicles that have limited automation and vehicles that are fully automated. Fully automated vehicles (Level 4 NHTSA) can drive on public roads without a driver. This allows for a system that can operate without any humans. For mobility, this has large consequences. It enables a distributed network of vehicles, e.g. 'robo-taxis' that drive from a central place to pick you up and drive you to your destination (Fagnant & Kockelman, 2014a). Robots can work at any time of the day, don't get tired and can be much more efficient in transportation than their human counterparts. On top of that, fully automated vehicles allow a new demographic to travel: the elderly and children. (Interview 1, 2015) This has consequences for mobility and travelled miles.

It needs to be noted that for this research, the lower levels (0-2) are not important enough. This research covers scenarios that are fully developed and automated. The status quo, Level 0 'No Automation', is not automated and thus not considered in this research. While it is theoretically possible that no form of automation in vehicles becomes prevalent, it is not within the scope of this research to consider that future. This research is meant to prepare for new technological advances, and looking at the status quo is not useful for that purpose.

The lower levels of limited automation, Level 1 and 2, are also not looked into separately. This is because they are stepping-stones towards Level 3 'Limited Automation'. Level 3 is the logical conclusion of adding more and more Level 1 and 2 systems to a vehicle. For example, Tesla's announced Autopilot feature is at NHTSA Level 2 (Combined Automated Functions), but is expected to evolve to a Level 3 limited automated vehicle (Tesla Motors, 2014). Both levels require a driver and thus a driver's license, so the vehicle falls under limited automation. However, as mentioned before, the difference between limited and full automation is large enough to consider. Google's prototype AV is an example of a fully automated vehicle. It has no steering wheel, operates completely on its own and doesn't require a driver to get around.

Concluding, there are two levels of automation that matter for mobility: limited automation and full automation. These two will be used to differentiate between vehicles with autonomous technology.

2.3. Mobility Type

The second factor that will be used to differentiate between automated vehicles is the type of mobility: personal mobility, on-demand mobility and centralized mobility. Each of the three has a different effect on mobility patterns, distance travelled, environmental impact, travel cost and time and many other factors. Automated vehicle technology allows these three to be developed simultaneously. The three mobility types differ mainly in the interaction between the user and the owner of the vehicle.

With personal mobility, the user is the owner of the vehicle. It is always available for the user and privately owned. The current use of cars is the most ubiquitous example of this kind of mobility. An example of automated technology in this category would be the aforementioned Autopilot feature on Tesla vehicles. It is a privately owned vehicle that has automation features. Multiple car companies are working on fully automated vehicles for personal mobility (e.g. Daimler, BMW, GM and Ford).

On-demand mobility is characterized by shared usage of vehicles. Where one user owning one vehicle characterizes personal mobility, on-demand mobility shares that vehicle with strangers. This can be through renting out privately owned vehicles (e.g. Snappcar), by renting distributed vehicles (GreenWheels, Car2Go, ZipCar) or by driving strangers around in your vehicle (taxis, Uber). Central to on-demand mobility is that the vehicle is nearby, either in the same community or the same city. It has to be, because the user needs to travel towards the vehicle (rentals) or the vehicle has to travel to the user (taxis). Automated on-demand vehicles, also called shared autonomous vehicles (Fagnant & Kockelman, 2014a) are estimated to provide great environmental benefits through efficient distribution of vehicles.

Centralized mobility is mobility that is controlled by organizations and governments, often with standardized routes and timetables. Whereas personal and on-demand mobility are initiated by the user, centralized mobility is independent of users. Whether a train will run is independent of whether people actually need to travel that day, as the train driver simply follows the timetable. Well-known examples of this are public transport and air travel. Automated examples already exist in the form of automated subway lines in cities like Paris, London, Vancouver, Hong Kong and Copenhagen.

2.2. Transport Configuration

These two ways of distinguishing automotive technology in vehicles can come together to create a holistic, inclusive view of automated vehicles. The two levels of autonomy on the one hand (limited automation and full automation) cover the technology spectrum of autonomous vehicles. On the other hand, automated vehicles are differentiated by the three main types of mobility they are used for (personal, on-demand and centralized mobility).

These different automated vehicles can evolve simultaneously (see figure 2). Personal automated mobility (e.g. Autopilot) might enter the market at the same time as autonomous centralized mobility (e.g. Wageningen).

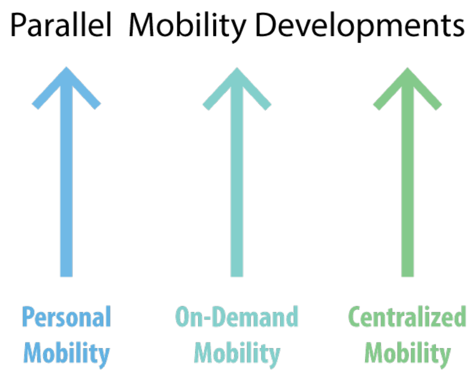

Figure 2, Parallel Mobility Developments

Because the type of mobility they deliver is different, they don't compete so much with each other as they do with the existing transport vehicles. As such, these three kinds of mobility can exist in parallel in the same transport system.

However, with the level of autonomy it doesn't work the same way. While it is possible to have automated and autonomous cars exist in the same configuration, it is likely that the higher form of autonomy is preferable to the automated vehicle. Full autonomous vehicles are better, safer, more efficient and likely cheaper than their automated counterparts. (Burns, 2013) They might be developed at the same time but it is very likely that a higher level of autonomy, if achieved, outcompetes the lower level automated vehicle.

A better model of the transport configurations, then, shows that the three types of mobility exist parallel to each other. It also shows the level of autonomy as progressive: from none to automated to autonomous. Hence the following conceptual model (figure 3):

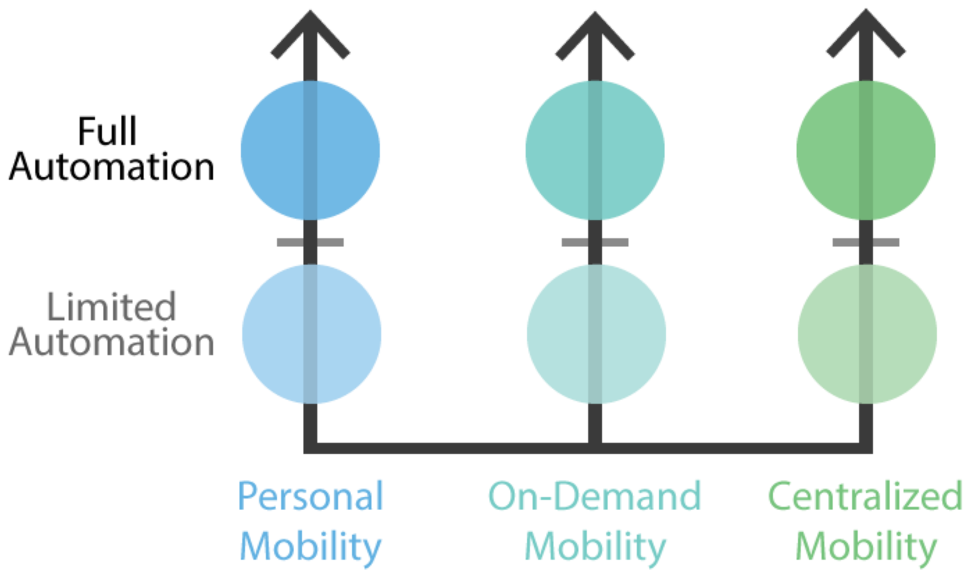

Figure 3, Conceptual Model for Autonomous Vehicle Scenarios

The vertical axis contains the gradual levels of automation. The three types of mobility exist parallel in the transport system. From this diagram, six areas of interest are distinguished. Note that the row 'No Automation' is excluded from this model: this is because no automation is the status quo, and not the focus of the scenarios. The six areas result in six scenarios, each scenario about one vehicle category, from the bottom left to the top right:

1. Personal limited automation vehicle (e.g. Tesla Model S)
2. Personal full automation vehicle (e.g. Google Car)
3. On-demand limited automation vehicle (e.g. GreenWheels)
4. On-demand full automation vehicle (e.g. Shared Auton. Vehicles)
5. Centralized limited automation vehicle (e.g. Automated Subway)
6. Centralized full automation vehicle (e.g. Wageningen, Rivium)

These six vehicles and their consequences will be explored in Chapter 4 in that order. For each vehicle type, a scenario is used: what is the impact of the vehicle type, if it were to become popular, on transport and on mobility? This is dependent not just on the vehicle but also on its place in the transportation system. By looking at the transport system in terms of transport *configurations*, it is possible to discuss the transport context that surrounds the autonomous vehicle. Modal split is one way of looking at the transport configuration. A configuration of the transportation system implies that every part of the system is interdependent. Transport configurations are also changeable by altering parts of the configuration. If, for example, on-demand fully automated vehicles become a seriously competitive alternative to taxis and buses, it is likely to reduce the role of regular taxis and buses in the transportation (system) configuration.

The scenarios will then aim to answer the following question: what will the impact be of scenario X on the transport configuration, if it were to be fully realized and ubiquitous? While multiple scenarios will likely unfold simultaneously, it is beyond the scope of this research to consider all the possible ways these scenarios might interact with each other. For example, while autonomous taxi's might work together with automated public transport, it is very difficult to predict how that might occur and what the consequences might be.

Chapter 3: Methodology

3.1. Scenarios

Scenarios are one of the most basic concepts in future studies. Using a scenario forms a good basis for assertive action (Bartholomew, 2006). It encompasses descriptions of both possible futures and possible developments (Borjeson et al, 2006). In his article, Borjeson describes three kinds of scenarios: predictive, explorative and normative. Predictive is about what is likely to happen. Explorative scenarios are more concerned with what can happen. Normative scenarios, lastly, are about reaching a specific target: how can a certain future happen?

Predictive scenarios are good at achieving depth in understanding the future. The more certain the predicted future is, the more useful the predictive scenario. If a predictive scenario is thought out and the prediction fails to occur, it diminishes the entire scenario. This is what is likely to happen with most of the current research on automated vehicles. Because they assume a certain kind of vehicle will 'win', the study is not very usefull when another kind of vehicle becomes popular. For example, MorganStanley research (2014) expects shared autonomous vehicles to be the future of automated vehicles. It is based on the assumptions that automation and carsharing are inevitable and will combine at some point in the future in the form of a shared car. If any of those assumptions doesn't work out as expected, the research loses most of its relevance.

Normative scenarios are similar to predictive scenarios. They put a kind of future as a dot on the horizon. The roadmap towards that future is then researched plotted. It's much more flexible, as it doesn't really matter how closely the roadmap is followed, as long as the desired result is achieved. However, it is not a great method for getting perspective on the future of automated vehicles.

Whereas the focus of existing literature is on the predictive and normative scenarios, this thesis will attempt to be more comprehensive by looking at explorative scenarios. A downside to the use of explorative scenarios is that it is hard to define when the scenario has unfolded. It is also important to thoughtfully consider which consequences are relevant and which are not. After all, anything can happen, and scenarios like autonomous vehicles have almost infinite consequences.

On top of that, explorative / extreme scenarios are pretty much always wrong. (Interview 3, 2015) It assumes full adoption of a certain technology, for example, which can almost never be accomplished. That does not mean the scenarios are worthless: in thinking of these extremes, one can prepare and think about a lot of consequences that one would otherwise be ignorant of.

While this research narrows it down to just the consequences on mobility, that too is an encompassing term. Mobility can be different on the individual level. This research will select some key consequences, mostly those that have the largest impact on the most people. Whether they're the best set of consequences to analyse this technology is up for debate.

3.2. Data Collection

The scenarios form the basis for in-depth expert interviews. The aim is to find an expert for most of the scenarios, so that the research gains depth in most scenarios. On top of that, it is the aim to find experts in different kinds of organizations: governmental, academic and commercial organizations. This gives a varied image of the subject and helps to find potential biases in the interviews.

The questions asked will have a similar goal as the research, meaning that they aim to assess and explore the scenarios and look at the consequences of those scenarios. First, the interviewee will be asked to explain his or her position in relation to the technology. What are they expecting from the technology? What do they do different from competitors / other actors, and why are they doing things different from them? How are they responding to trends?

Then, the specifics of the scenario(s) relevant to their position will be discussed. What is their end goal? How do they want the technology to develop? What are the consequences of that scenario? For whom is the scenario beneficial? Who gets left behind? The interviews will be recorded and stored safely. The interviewee will receive the audio file and a transcript if they so desire.

For additional literature, a combination of broad searches and so-called 'snowballing' is used. Firstly, articles related to the keywords 'autonomous vehicle', 'automated vehicle', 'self-driving car' and other synonyms were found. These articles often have a small set of keywords in their documents, which were used to find more broadly related articles.

To get more into detail on a certain subject, the sources of an article were researched, each article leading to more new sources. This method is called 'snowballing'. Some publishing platforms like ScienceDirect have a 'Related Articles' section next to each article, which yields similar results. Snowballing can be a very good method for going deep into a certain topic, but should only be used in unison with a broader search method.

Chapter 4: Scenarios and consequences

This chapter will discuss the characteristics of each scenario and their consequences in a structured manner. First, it is necessary to explain and demarcate the scenarios. What kind of vehicles fall under it? Secondly, the consequences of this scenario are explored. Three kinds of consequences are explored: consequences for travel behaviour and for the transport configuration, the resulting consequences for safety and the environment and finally a concluding statement is made on the probable impact of the scenario on mobility.

4.1. Limited Automated Personal Mobility

Limited Automated Personal Mobility covers all the vehicles that are automated under specific conditions and are used for mobility on the level of the individual vehicle. This covers mostly cars with driver assistance functions, ranging from simple lane centring functions to the much more technologically advanced highway automation. A definition could be 'privately-owned vehicles used mostly for the mobility of the owner, assisted by automated functions'.

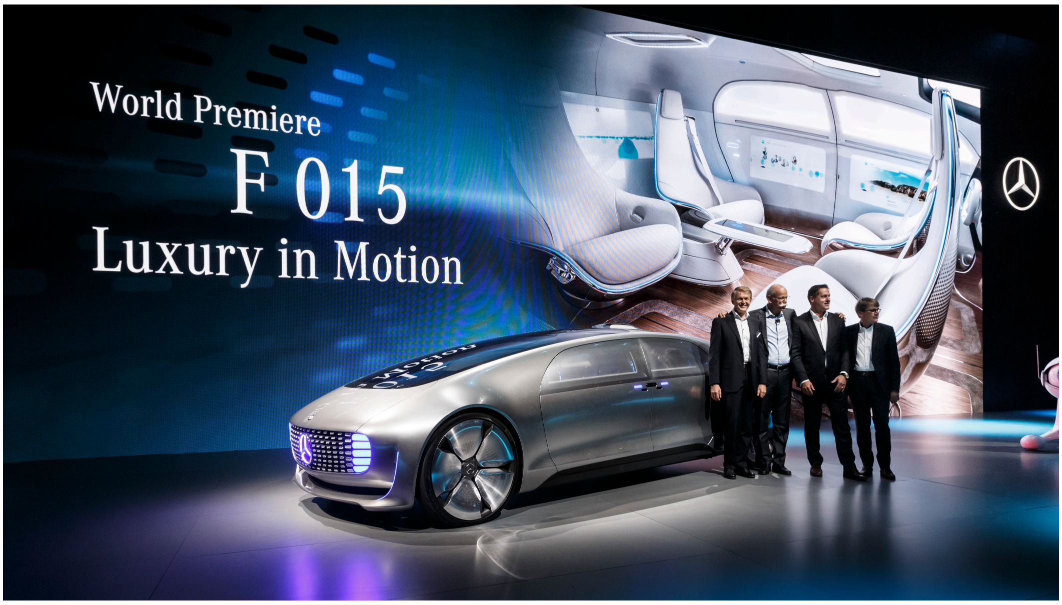

Figure 4, F015 premiere. Image: Mercedes Press Release

Most of the efforts now made by car and tech companies fall under this definition. Companies including but not limited to Tesla (Tesla Motors, 2014), Google, Daimler, Volvo, Nissan, GM, BMW and Delphi (Burns, 2013) are working on automating some part of driving. Google, for example, has already driven over a million kilometers with their fleet of automated Toyota Prius and Lexus vehicles (Urmson, 2014). Full highway automation in cars is estimated to hit the market in the next five to ten years (Interview 2, 2015). Tesla already launched the first version of their Autopilot function (Tesla Motors, 2014), which can take over highway driving under the right circumstances. Daimler recently showcased their Mercedes F015 prototype (see figure 4). It is their vision of automated personal mobility. It still has a steering wheel, but can also be driven like a normal car.

For travel behaviour and mobility, a few characteristics of these vehicles are important to note. Firstly, they are based on regular cars and thus all require a driver's license. Even though the goal is to automate as much of the driving process as possible, an automated vehicle can and probably will always be dependent on a driver. The transition from automated to regular driving is also a difficult problem, which institutions like the TU Delft are trying to solve (Interview 2, 2015). It takes at least four seconds for a person to take over the wheel, at least eight seconds before the driver can respond adequately and it takes around thirty seconds before the driver has the same precision as a regular driver (Interview 2, 2015). This means that the car has to be able to safely drive itself for multiple seconds in the situation where the car has the most difficulty driving. This might pose a great challenge for the safety of the automated vehicle.

Secondly, most automated vehicles are based on non-automated vehicles, adding the automated features incrementally (Anderson, 2014, p. 117). The simplest form of automation is functions like cruise control, whereas the most advanced automation would allow the user to take the hands off the wheel for over 90% of the time. The mobility pattern of personal automated vehicles is mostly influenced by the percentage of a trip that is automated. For this scenario, it is assumed that automated cars become the standard and that they have automated functions to such an advanced degree that the majority of the drive has been automated.

What then might some of the consequences be? Automated personal vehicles are not much different when it comes to travel behaviour compared to their non-automated counterpart. Its main benefit is that it allows people to do other things while driving, e.g. working or consuming media. The former might have the effect that people can live further from their jobs. If 90% of a drive is automated, employees might consider living in rural / suburban areas and work while they drive. This leads to an increase in the amount of vehicle kilometres driven. Its role in the transport configuration might thusly change because of the increased attractiveness of using a car. A car where you don't have to drive for most of the trip is a serious competitor for train travel. It could cannibalize public transport. (Interview 2, 2015)

The environmental consequences of this scenario are mostly found in efficient driving. Automated vehicles can drive closely behind each other in a train of vehicles (aptly called 'platooning'). This is estimated to provide around 10% fuel efficiency (Brown, 2014), and around 5-7% in trucks. (van Lieshout, Alleen de eerste wordt bestuurd, 2015) Automated vehicles can also accelerate and decelerate smoother, which provides an additional 4-10% fuel savings depending on the environment. (Anderson, 2014, p. xvi) Currently, there is also a trend of 'connected vehicles', whereby vehicles can talk to each other (Vehicle to Vehicle, V2V) or to infrastructure (V2I) using DSRC, dedicated short-range communications (KPMG & CAR, 2012, p. 12).

Finally, automated functions can save a great deal of lives if they become widespread. Computers can be much quicker at recognizing and responding to threats or imminent crashes. Daimler's cars can already go from sensor input to braking and/or steering in just 300 milliseconds. (Gavrila, 2015)

For mobility, the automated personal vehicle has the largest impact on long-distance drives. It will impact the current long-distance trains and buses significantly. People can live further from their jobs, as they can work better while commuting. However, it is likely that the user will still need to drive at least some part of the trip for the foreseeable years. Once that isn't needed any more, a lot of new benefits and consequences come in play with the fully automated personal vehicle.

4.2. Fully Automated Personal Mobility

The fully automated personal vehicle is an important step up from the automated personal vehicle. The main difference is that a fully automated vehicle can drive without human control. This kind of vehicle does not require a driver's license: all aspects of moving the vehicle through space and time are done on its own, except for the start and end position, which the user determines. Because this is personal mobility, the vehicle is owned by its primary user and parked near or on the user's property.

An example of this would be the recent Google prototype (figure 5). After working mainly on Level-3 automated technology fitted on Prius and Lexus cars, the company unveiled a prototype last year (Urmson, 2014). The vehicle, a small two-seater, is the first vehicle that can do almost all aspects of driving completely automated. It has no steering wheel and only has a red 'panic' button in case the user wants the vehicle to stop. Because it is an early prototype, it is a small two-seated vehicle with its speed capped at 40 km/h. However, there is no theoretical reason why this sensor-computer combination can't be equipped on larger and faster vehicles. The sensors on this vehicle are almost identical to the sensors on the Prius and Lexus cars.

When it comes to travel behaviour, the most trivial implication is the new demographics that such a vehicle mobilizes. It gives total freedom of mobility to children, the elderly, the blind and many other groups who either can't drive, didn't

Figure 5, Google's Self-Driving Car. Image: Google want to drive or weren't allowed to. Mobilizing such a large demographic is estimated to lead to a 40% increase in vehicle usage. (Brown, 2014) It also shares much of the changes in travel behaviour with the automated personal vehicle, in that it can also operate in platoons and can drive more efficient over longer periods of time.

There are two ways the fully automated personal vehicle can be a big threat to the existing transportation configuration. If the sensor technology becomes cheap enough to be fitted on small cars similar to the prototype, it could compete directly with bikes and public transport for urban trips fewer than 10 kilometres. If it is mostly fitted on regular-sized cars, it poses a great threat to public transport in general. The latter scenario, in combination with the sharp increase in mobility because of the new demographic could lead to serious road capacity issues. Whether fully automated personal mobility becomes popular through small vehicles or through regular cars, it alters the transportation configuration heavily towards car and road usage (Interview 2, 2015).

The consequences for safety are drastic. Google expects their car to be able to reduce the amount of accidents by over 90%, as most errors leading to accidents are human error (Urmson, 2014). Removing people from the equation entirely, which full automation allows, could create vehicles that are much safer than those driven by people. The more vehicles are fully automated, the safer they become as they could communicate with each other.

The environmental consequences are just as big. Brown (2014) estimates that the use intensity might see a net increase of 86%, the needed energy a net decrease of 42% and the needed fuel a decrease of 75%. The net effect of such vehicles is positive, although they do put a large strain on the road network and increase the amount of vehicle miles per year significantly. This does depend on whether these vehicles will be optimized among each other. Platooning fully automated vehicles could improve road efficiency by a great deal.

For mobility, full autonomy has obvious benefits, as it mobilizes a much larger demographic. It could completely remove the need for public transport drastically. Mobility would become much more individual, with everyone riding around in their own personal fully automated vehicle.

4.3. Limited Automated On-Demand Mobility

On-demand mobility is mobility only when you need it. Also called 'mobility as a service', this scenario covers two kinds of shared vehicles: the vehicles you can rent (GreenWheels) and rides you can rent (Uber, taxis). Both are mobility on demand, and both vehicles have to be requested by the user, which differentiates them from personal and centralized mobility where this action is not needed. If users don't specifically want to make a trip, the vehicle is not used. In the case of carsharing, the user needs to make a short trip to get to the car. With taxis, the driver needs to make a short trip to pick up the user, or the user walks to a taxi-stand.

Car-sharing services have been growing almost exponentially (Shaheen, 2006). With initiatives like Car2Go, Greenwheels, Zipcar and Snappcar, more cars are being shared every year. To have successful on-demand mobility, accessibility and the distribution of vehicles is key. The main advantage of carsharing is the effective use of vehicles that are not used anyway. It has been estimated that at any given moment, only 10% of all vehicles are in use, with the other 90% taking up parking space (Federal Highway Administration, 2009). Taxis, on the other hand, have the advantage of a uniform fleet of vehicles and drivers. They can guarantee quality service and can use easy per-mile payment.

Adding automation to the mix has direct consequences on the travel configuration. For taxi's, long-distance rides become much cheaper to operate because of fuel savings. Taxi's might become competitive with trains because of this, especially as a replacement to multimodal travel. Automation in shared cars has a similar effect on travel behaviour as the personal limited automated vehicle: it makes long-distance car driving much more attractive, it can decrease the importance of trains and allows people to do other things while driving. Carsharing has the added benefit of dispersing the investment cost of owning a car. Currently, cars are the most expensive commodity bought by consumers and automation features are only found on the more expensive segment of cars. While the features are expected to 'trickle down' to cheaper models (Interview 5, 2015), this might not occur because of the complexity of the systems and sensors. However, the cost of owning and maintaining a vehicle can be covered partly with carsharing. Carsharing makes automated vehicles more attractive to own, and automation makes them more attractive to use. As policy expert Ad van der Have noted, "people just want to get from A to B. How they get there doesn't matter, as long as it is fast and cheap" (Interview 1, 2015).

The safety benefits of on-demand limited automated vehicles are similar to that of the personal limited automated vehicle. Carsharing does not change safety beyond the safety benefits of limited automated driving.

The environmental consequences are mostly in the efficient use of vehicles. Instead of five people driving their cars 20% of the time, those five people could share one car. The automation functions also allow for more efficient, longer drives. It also has the benefit of fully demand-based mobility: there are almost no unnecessary trips made, as opposed to centralized mobility. A bus will drive even when nobody is using it, but a taxi or shared vehicle only drives when a trip is made.

Concluding, limited automated on-demand vehicles bring the advantages of carsharing to the limited automated personal vehicle, and bring the advantage of automation to taxi's. This means that mobility becomes a service. It is completely demand-based and centers on the user.

4.4. Fully Automated On-Demand Mobility

The scenario of fully automated on-demand mobility covers mostly the so-called 'shared autonomous vehicles' (SAV's) and autonomous taxis, aTaxis. These vehicles can drive on their own and can be summoned by the user. They can be owned either by a company (e.g. Uber, Car2Go, GreenWheels and taxi companies) or by people in the area (e.g. Snappcar, Zipcar).

Adding full automation to on-demand vehicles blurs the line between taxis and shared vehicles. This is because bringing the vehicle and the user in one place can now be done by the vehicle itself, instead of by a driver or by the user having to walk to the vehicle. Currently, the most attractive walking distance to a shared car is up to 200 meters (Car2Go, 2013). Most cars beyond that perimeter are too far to provide mobility. With SAV's, vehicles far beyond the 200m range can drive to the user. This means that much less vehicles are needed compared to regular carsharing services.

SAV's have a plethora of benefits. Spieser et al. (2014) calculated that if all private mobility in Singapore were replaced by SAV's, two-thirds of the vehicles could be removed. It also concludes that the total vehicle distance travelled will greatly increase. Recent research by Martinez (2015) expanded upon this research by looking at two types of autonomous on-demand vehicles: 'TaxiBots' and 'AutoVots'.

Autovots pick up single users sequentially, whereas several passengers can share TaxiBots simultaneously.

They estimated that with rides being shared by different users in TaxiBots, 9 out of 10 vehicles could be removed while still maintaining mobility. In the best scenario, taxibots combined with good public transport, such a system would lead to a mere 6% increase in car-kilometres travelled. The worst scenario, AutoVots in the absence of public transport, would "nearly double (+89%) car-kilometres travelled" (p.5). This example shows that the environmental impact of autonomous on-demand can greatly differ when used in different transport configurations. For transport within cities, fully automated on-demand vehicles can either work with or compete with public transport.

Regardless, if it becomes technically possible and attractive form of transportation, fully automated on-demand vehicles will bring about large changes to the transport configuration. They can completely replace buses and taxis as we know them now. Even if it isn't the fastest option available, fully automated on-demand vehicles could operate for way less per ride than regular taxis or carsharing services (Fagnant & Kockelman, 2014b). Estimates put the cost of the on-demand vehicles between $0.18 and $0.34 per mile (Burns, Jordan, & Scarborough, 2013). For comparison, Car2Go operates at $0.41 per mile and a regular car costs approximately $0.50 per mile (not including parking).

As mentioned, the environmental benefits are completely dependent on the type of vehicle and on its role in the transport system. It also depends on whether the vehicles are electric or still have an internal combustion engine. For urban space, this scenario will remove the need for almost all parking (Interview 5, 2015) and will change the nature of emissions completely. It is likely that the benefits still outweigh the disadvantages of the added vehicle miles in a scenario where autonomous on-demand vehicles are operating (Fagnant & Kockelman, 2014a).

The safety benefits are clearer, though. Replacing most personal mobility with autonomous on-demand mobility goes a long way to reducing accidents, which are most likely to happen in cities. Because one vehicle might drive all day long, the autonomous fleet has a replacement rate of around 2 years (Martinez, 2015). This allows new (safety) technologies to be implemented much faster than with other vehicles, which often have a replacement rate of two or more decades.

Concluding, the consequences for mobility are potentially immense. On-demand fully automated vehicles allow anyone to summon a cheap ride in cities. It is mobility as a service, but for everyone – not just those with driver's licenses. If the rides are shared, it allows the combination and optimization of trips, which could lower the costs even further. The amount of miles travelled might increase drastically, with serious consequences for the available infrastructure. While fully automated cars can drive closer behind each other, this advantage is likely negated by the much larger increase in mobility.

4.5. Limited Automated Centralized Mobility

One organization or company controlling a fleet of vehicles according to a predetermined timetable characterizes centralized mobility. Examples of this are public transport and commercial air travel. Within this category, a wide variety of vehicles exist: subways, trains, light-rail, airplanes, buses, trams and others. All vehicles have drivers or pilots, which automation can assist. Currently, automation is most common in airplanes (which can take off, fly and land on autopilot) and rail-based transport (e.g. subways). It is entirely possible that other vehicles like buses and trams get automated using similar technologies. This scenario assumes that current centralized mobility vehicles are automated to such a degree that most of the driving is done by autopilot.

Rail-based vehicles are already capable of being automated. As with cars, there are multiple grades of automation (GoA) (UITP, 2015), ranging from GoA 1 (no automation) to GoA 3 (has train attendant to open doors and for emergencies) and GoA 4 (fully autonomous). Systems like London's Docklands Light Railway are GoA 3 and fully automated but not autonomous as they still require a train operator. The advantages of these systems are that they operate more efficient, increase safety, are on time and require less manual labour. There are no examples of automated rail-based vehicles that cross with regular traffic, like trams and trains. This is likely due to the cost of installing such a system and the difficulty of spotting dangers in time. Subways are closed environments and are much easier to automate. Trams and trains could be equipped with technology from automated cars (to spot dangers) and subways (automating doors, movement etc).

The same goes for buses, although automation is less likely to occur. This is because the largest costs of automation are in the technology behind it. Buses can carry less people and encounter much more complex scenarios than trains or trams. Long-distance buses (e.g. between cities) might benefit from highway automation. This leads to the aforementioned 10% reduction in fuel usage. Because the bus driver doesn't have to pay as much attention when the autopilot is on, they can drive vehicles on longer trips and work longer shifts. The biggest advantage limited automation could bring to buses is linking multiple buses to one bus driver in a platoon. Currently, tests are being done in Zwolle with trucks whereby three trucks closely follow one truck and copy the behaviour of the first truck, which holds a truck driver (van Lieshout, 2015). Platooning linked buses might compete with trains, as a platoon of a handful of buses can be operated for much less than a costly railway line.

In general, the advantages of this form of automation are limited for mobility. Developing the technology to automate public transport has relatively few benefits compared to fully automated centralized mobility.

4.6. Fully Automated Centralized Mobility

The scenario of fully automated centralized mobility covers all vehicles that are operated by a central organization or company, can drive around fully automated and often go around on a predetermined route. These vehicles don't require a driver or operator and can perform all actions on their own.

An example of this already in effect is the ParkShuttle in Rotterdam. This shuttle drives between the subway station Rotterdam Kralingse Zoom and the business park Rivium (figure 6). The automated people movers drive every two and a half minutes in rush hour and are on-demand outside of rush hour. They follow a predetermined path, on separate infrastructure. Even though it doesn't go on public roads, it is a good example of future transportation might look like.

Figure 6, Rivium shuttle. Image: Wikipedia

There are numerous examples of closed-circuit fully automated vehicles, most often as people movers in airports. But there are also projects underway that hope to provide a similar experience without expensive infrastructure and on public roads. A notable example is a project started by the Gelderland Province in cooperation with Wageningen University and Delft University of Technology. Their aim is to perform the first fully autonomous tests this December. The vehicle will start by driving around the public roads on the Wageningen Campus. If successful (read: safe enough), the route will be expanded in stages towards the Ede-Wageningen train station. (Interview 1, 2015) The goal is to have a working shuttle that can drive fully automated on public roads in the next years. "The technologies are there – what's difficult is bringing them together to steer the vehicle" (Interview 1, 2015).

It is imaginable that most – if not all – of public transport is replaced by these shuttles. While door-to-door transportation is more interesting and has more benefits, replacing buses and even trams / trains with these vehicles has its advantages. Its main advantage is that it can follow a predetermined path. With the fully automated on-demand vehicle, the vehicle needs to be able to tackle any street and any intersection in a city from every direction. It needs to be able to handle pretty much anything a city throws at it. But a shuttle service can be optimized. The Wageningen vehicle will start on just a small part of the route. Because the vehicle travels the same route again and again, its understanding of the route is very high. As soon as that part is fully understood, it can expand its route. (Interview 1, 2015)

What would the consequences be of such a scenario? First of all, it will enable public transport to have more vehicles drive at more hours of the day for more people. More 'bus' lines can be operated and at higher frequencies. It can reduce the cost of public transport dramatically. Driver wages and rolling stock are two of the biggest expenses in public transportation. Full autonomy will reduce the amount of labour and the smaller vehicles can be made cheaper and can be tailored better to the actual transportation needs.

For the transportation configuration, this means that public transport becomes a much more attractive option. Car usage could decline, and Park & Ride solutions become much more attractive if the bus ride is much cheaper and more frequent. In the long run, regular cars might be banned from (inner) cities entirely (Interview 1, 2015), as a dense network of fully automated and frequent vehicles can replace regular traffic similar to the fully automated on-demand vehicle. Fully automated centralized vehicles also have the advantage of better connecting rural areas. The village of Appelscha, for example, wants to explore the use of a fully automated vehicle 'as a solution to maintaining bus routes in rural areas'. (Leeuwarder Courant, 2015)

The safety aspect of this scenario depends on how safe full automation will become in busy and dense urban centres. A lot of accidents happen there – for example, a bus driver who didn't see a bicycle. While sensors can spot people quicker and can spot more at the same time than a human, predicting what each person will do might be a very difficult and complex task.

Environmental consequences will most likely be dependent on the vehicle actually in use. A bigger, denser, more frequent network of smaller vehicles like the aforementioned Rivium line has the obvious downside of increasing the amount of vehicle miles travelled by public transport. However, efficient planning of lines and the use of electric vehicles can make these lines very efficient, with rarely any empty seats and low emissions per mile travelled. Because the rides are shared and because they make cars less attractive, it is very likely that the overall vehicle miles travelled will decrease. For mobility, this scenario can provide significant improvements in (public) transportation both in urban and in rural contexts. More service in more areas of better quality. This can convince people to travel more by centralized transport methods such as buses and trains.

4.7. Conclusion

The consequences of each scenario are summarized in figure 7:

Scenario	Effect on transport configuration	Effect on envir. and safety	Effect on mobility
Limited automated personal vehicle (e.g. Autopilot)	Decrease train/bus usage, increased car usage. Long car trips more attractive.	More long trips made, but they are more efficient and safer.	Increasing long-distance travel / commute
Fully automated personal vehicle (e.g. Google car)	Replace public transport entirely, road usage increases	Drastic increase of usage and intensity. Can reduce walking and bike trips.	Everyone can drive their own automated car. More mobility for more people.
Limited automated on-demand vehicle (e.g. GreenWheels)	Same as limited automated personal vehicle	More efficient use of cars, less vehicles needed	Carsharing gives people without a car more mobility
Fully automated on-demand vehicle (e.g. aTaxi)	Could potentially replace almost all types of mobility because it is cheaper and door-to door	Competes directly with more env. friendly modes of transport. If it has no ICE, it might be a net benefit.	Ubiquitous mobility, for everyone and everywhere for cheap.
Limited automated centralized vehicle (e.g. automated subway / trains)	Automated improvements on current public transportation and airplanes	Mostly safety benefits, some efficiency improvements	Allows more frequent service
Fully automated centralized vehicle (e.g. Wageningen, Rivium)	Replace current bus / train network with fully autonomous vehicles. Could replace cars in cities entirely.	Smaller and more efficient vehicles can have a smaller footprint	More dense, safe and frequent network in urban areas. Could provide better and cheaper public transport to rural areas.

Figure 7, Summary of Findings

Chapter 5: Conclusion

This chapter will briefly discuss the findings, relate to other research and present some ideas for future research. The goal of this research was to explore the impact of different scenarios of automated vehicle technology. Based on two factors (mobility type and level of automation), six important scenarios were distinguished. The impacts of the scenarios differed greatly.

Personal automated vehicles can make road travel much more competitive and important. They can have a great impact on public transport. The vehicles can increase road use if they drive outside of platoons and increase emissions dramatically if they have an internal combustion engine.

On-demand automated vehicles place the user at the core of mobility. These vehicles only drive when they are needed. Efficient use of vehicles is central to the scenario, and it is likely the cheapest form of transportation because of that.

Centralized automated mobility can lead to a denser, more frequent net of (public) transport vehicles. It can make cars in cities obsolete, and can revitalize rural centralized transport.

One of the experts mentioned that it is not so much the technical aspect of automated technology that's interesting – rather, it is the impact on the actual world that matters (Interview 5, 2015). Part of the goal of this research has been to explore some of the impact on the actual world.

There are three major takeaways from this research. Firstly, it is that the impact of automated technology is highly dependant on the kind of vehicle. The impact of a limited automated car scenario is completely different than an on-demand fully automated vehicle, both for the environment as for the transport configuration.

Secondly, it is that the impacts are really hard to predict. Multiple interviewees used the term 'koffiedik kijken' (gazing) when talking about possible futures (Interview 1, 2015) (Interview 4, 2015). The consequences for the transport configuration are the hardest to predict, as it is dependent on a plethora of factors. This is one of the flaws of explorative research on an unpredictable topic. 'There is no single truth' (Interview 3, 2015).

Thirdly, efficiency and safety are the central themes among the results. They are often the reasons organizations give for pursuing autonomous technology in the first place. It is the efficiencies that make cheaper transportation –and thus, the investment- worthwhile. It is no wonder then that a lot of the current research is focused on the potential efficiency benefits, e.g. (Fagnant & Kockelman, 2014a). The most efficient scenarios are also the most competitive, as the efficiencies allow the technological costs to be greatly reduced.

Interestingly, during the interview with the Dutch Ministry of Infrastructure it became apparent that they are using a similar approach to this thesis. (Interview 3, 2015) While they use a more classic scenario model with quadrants, they have also assessed the level of autonomy as an important distinguishing factor and are also using an explorative approach. They have four scenarios and use more assumptions, but the methodology is similar to this thesis.

This research could be expanded upon by taking a closer look at each of the scenarios, e.g. by talking to more industry experts and major market players like Tesla, Google and auto companies. It would also be interesting to look more at the human aspect of the technology: how will users respond and interact with different kinds of fully autonomous vehicles?

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