TU Delft

Spatial and Transport Impacts of Automated Driving

Master Thesis

Infrastructure Requirements for Automated Driving

Xiaolin Lu

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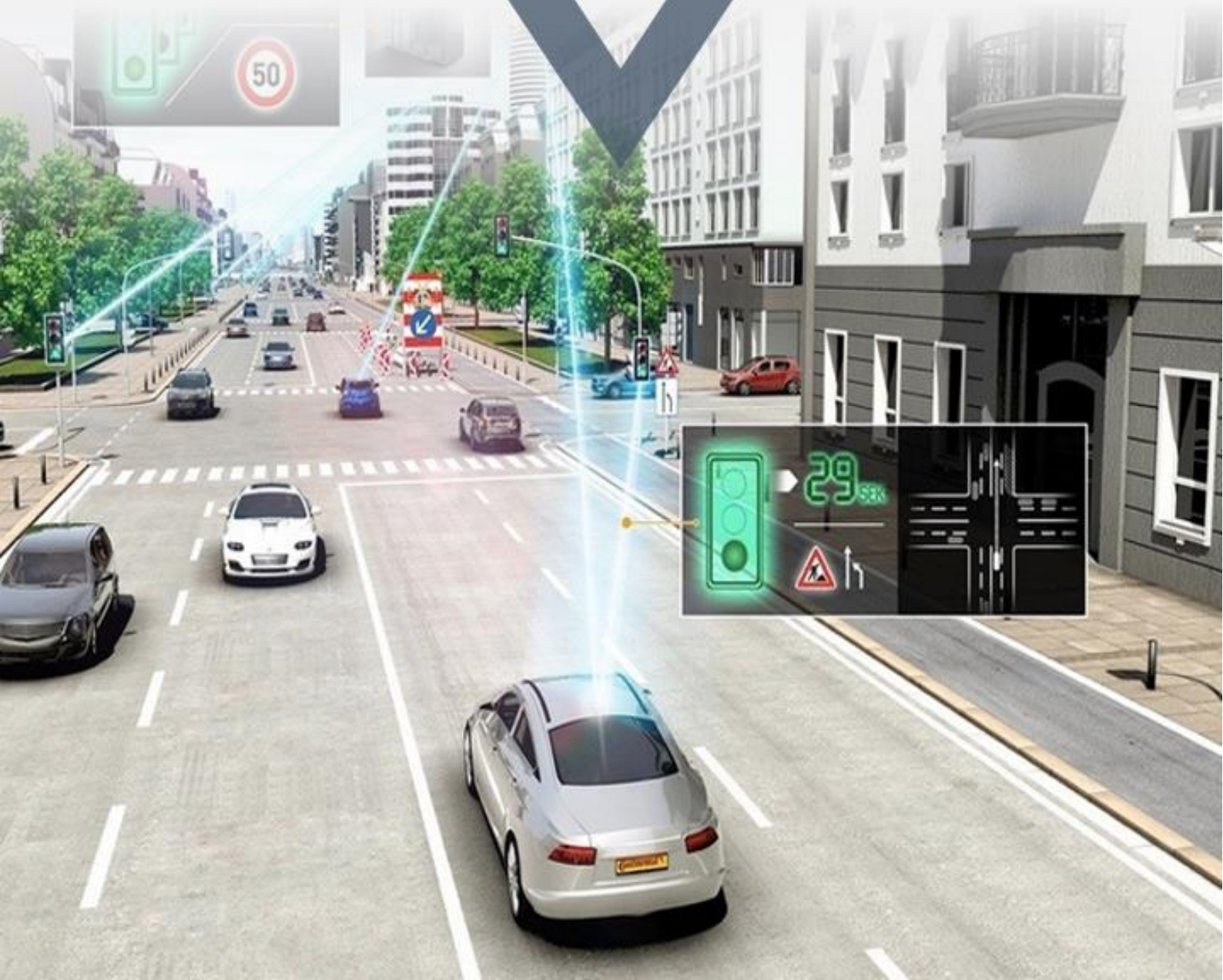

Infrastructure Requirements for Automated Driving

BY

Xiaolin Lu

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Author: Xiaolin Lu

Email: seuluxiaolin@hotmail.com

Graduation Committee:

Prof. dr. ir. B.(Bart) van Arem	TU Delft, CEG
Dr. ir. H.(Haneen) Farah	TU Delft, CEG
Dr. M.(Maaike) Snelder	TU Delft, CEG
Dr. J.A.(Jan Anne) Annema	TU Delft, TPM
Msc. B.(Bahman) Madadi	TU Delft, CEG

TU Delft

Spatial and Transport Impacts of Automated Driving

Preface

This report is the result of my graduation thesis as a completion of the master Construction Management and Engineering at the Delft University of Technology. By combining the knowledge of Construction Management, which is my main study content and Transport and Planning, which I am interested in, I finished this research. This report also means the end of my two-year's master study in the Netherlands.

The research process is always full of challenges and difficulties. I would like to thank everyone who contributed to this research and gave me a hand when I felt stressful and even hopeless.

Firstly, I would like to express my gratitude towards my committee members. Bahman, thank you for your daily supervision. After every meeting with you, I gained a lot and come up with new ideas to continue this research. Thank you, Dr. Haneen Farah and Dr. Maaike Snelder, for your offering me such an interesting research topic and helping me to contact interviewees. Thank you, Dr. Jan Anne Annema, without your suggestion on using scenario planning approach, I may spend more time on deciding the suitable research method. Thank you, Prof. Bart van Arem, it is your lecture for the course *Assessment of Transport Infrastructure and Systems* that gave the first perception of automated driving. Your feedback on each formal meeting and your enthusiasm encouraged me a lot.

Then, I need to thank all the fourteen interviewees for their time, hospitality, and your willingness for sharing knowledge with me. I also want to show my thanks to my seniors, Yan Liu and Hai Gong, they helped me to prepare the research proposal and review the final report.

Afterwards, I want to thank my friends and my boyfriend. We studied together and played together for the past two years. I will remember our mutual experiences forever and wish you great careers.

Lastly, I want to thank my parents for giving me the opportunity to study abroad and support every decision I make.

Xiaolin Lu

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Executive Summary

Research Problem

In the past few years, the research and development of automated driving have made significant leaps in bringing theory into reality. It is predicted that highly automated vehicles (SAE level 3, 4 & 5) will be on the streets and highways within the next decade. However, current road infrastructure is designed for human drivers, and may not be able to deal with the integration of high driving automation level vehicles. Enabling automated vehicles to travel along the public roads may need infrastructure upgrades or adjustments based on requirements of automated vehicles. However, the minimum requirements for the infrastructures are not yet clearly defined. Few researches are available on the infrastructure requirements for automated driving (Nitsche et al., 2014; EU, 2016; Farah et al., 2016; CATAPULT, 2017; Lawson, 2018) and the amount of complete or on-going projects addressing infrastructure for automated driving is limited (Vreeswijk, 2018; Harrer, 2018; Lytrivis, 2018). In addition to the lack of theoretical and practical reference, how to implement infrastructure requirements under unpredictable future situations is also an obstacle for road authorities when they need to make the decision among a set of alternatives.

Research Scope and Research Question

As Level 5 will not be on roads before 2075 (Shladover, 2015; SWOV, 2016; TNO, 2016) and Level 3 is problematic because of the difficulty to attain drivers' attention after being out of the loop (Shladover, 2015; Farah, 2016; SDFE, 2017), this research aims to investigate potential infrastructure requirements for SAE Level 4 automated driving under possible future scenarios. Both physical and digital infrastructure will be involved, and the research scope includes motorways and provincial roads where may be first allowed for automated vehicles (CROW, 2016).

To address the problem statement explained in the previous section and the research mentioned above objective, the following research question is proposed:

What are the road infrastructure requirements to allow for SAE Level 4 automated driving?

Research Approach and Findings

Five steps are applied to complete this research.

Step 1 is to understand the research status and market status of infrastructure and automated driving, containing literature review and stakeholder analysis.

- Research status of infrastructure requirements for automated driving

Through reviewing the scientific literature on infrastructure requirements for automated driving, it is found that they come to some same conclusions: lane markings and road signs should be readable for automated vehicles, V2I technology will play an important role in the future and there may be a trend of transition from physical infrastructure to digital infrastructure (Nitsche et al., 2014; Farah et al., 2016; G0V-CN, 2018; The U.S. Department of Transportation, 2017; JAMA, 2018).

Compared with studies on digital infrastructure, the literature on physical infrastructure is lacking. Another drawback of those studies is that most of their information resources are scientific literature and experts' thoughts which lack opinions from manufacturers and have limited practical significance. Another weakness is that they do not take different future scenarios where infrastructure requirements may also differ into account.

- Market status of infrastructure for automated driving

The stakeholder analysis is conducted to study the market status of infrastructure for automated driving. Seven stakeholders are involved in this issue: Vehicle authorities, Manufacturers, Service providers and suppliers, Research Institutes, Car drivers and Insurance companies. Through analysing their interests, power, goals and resource dependencies, five of them are defined as critical stakeholders whose involvement Levels are higher in this issue. They are The Ministry of Infrastructure and Water Management (Dutch context), Road authorities, Vehicle authorities, Manufacturers, Service providers and suppliers and Research Institutes.

As different stakeholders have different core values and concerns, the market status of infrastructure for automated driving is quite complex. Hence, to implement infrastructure upgrades for automated driving smoothly and successfully, stakeholders need to be engaged and the whole decision-making process should be open and flexible. Byson's (2004) five levels of stakeholder involvement (Inform, Consult, Involve, Collaborate, and Empower) is undertaken as stakeholder engagement strategies. The Ministry of Infrastructure and Water Management has the authority to decide public expenditure for infrastructure upgrades, so the level of involvement is the highest-Empower. Road authorities will take the role as coordinators and executors during the implementation phases, therefore, their level of involvement is Collaborate. According to manufacturers' willingness to share their information and knowledge, the level of involvement could be Collaborate (strong willingness to share) or Involve (weak willingness to share). Service providers and suppliers also need to be Involved, as they can figure out whether those infrastructure upgrading solutions can receive technical or raw material support. For the other two critical players, the level of involvement will be Consult because their expertise and resources can be beneficial for addressing this issue.

Step 2 aims at developing future scenarios regarding automated driving and infrastructure as well as defining specific road situations where infrastructure requirements for automated driving may differ. The scenario planning approach is applied and specific road situations come from the results of the literature review.

- Four Scenarios

The construction of four scenarios follows the logic of Peter Schwartz's (2004) methodology with fewer steps to simplify the process. Due to the highest impact on infrastructure for automated driving and uncertainty in the future, economy and stakeholders' attitudes are used as top two driving forces to build the scenario matrix. With the scenario matrix, four scenarios describing the future of infrastructure for automated driving are known:

Scenario 0-Do-Nothing Scenario (Low Public Expenditure and Loose Cooperation)

- No requirements will be mapped into this scenario
- AVs are only allowed on specific sections of motorways or provincial roads under a certain Level of maintenance

Scenario 1-Basic Infrastructure Scenario (Low Public Expenditure and Close Cooperation)

- -Minimum requirements for ensuring traffic safety will be mapped into this scenario
- -AVs are restrained on upgraded sections

Scenario 2- Intermediate Infrastructure Scenario (High Public Expenditure and Loose Cooperation)

- -High-cost requirements will be mapped into this scenario
- -AVs are allowed on most motorways and provincial roads after upgrading

Scenario 3-Advanced Infrastructure Scenario (High Public Expenditure and Close Cooperation)

- -All feasible requirements will be mapped into this scenario
- -Automated vehicles are allowed on all motorways and provincial roads

These scenarios are validated by experts interviewed in the following steps. Based on reflections from experts, **Scenario 1 (Basic infrastructure) and Scenario 3 (Advanced infrastructure) are the two most likely scenarios**. They hold the view that Scenario 0 (Do nothing) is unacceptable due to its unsafety and Scenario 2 may not happen because the government will never invest in any projects without information and support from other parties. The regional difference and time period difference is also mentioned by those interviewees. Scenario 1 (Basic infrastructure) is more likely to happen in recent years and in countries where government revenue is limited. Scenario 3 (Advanced infrastructure) is more suitable to describe the situation of a country whose government strongly support the development of automated driving or the final goal of this issue (upgrade infrastructure for automated driving).

- Specific road situations

To partition specific road situations, this research studies road design manuals, literature on road design and automated driving, disengagement report of automated vehicle road test and the environment perception technology of automated vehicles.

In the end, four segments which represent typical motorway situations and four segments regarding provincial roads make up the specific road situations. They are: motorway-straight segment, curve segment, weaving area and exit/entrance; provincial road-unsignalized intersection, signalized intersection, roundabout and roundabout with bicycle lane.

Based on interviewees' responses, **motorway exit/entrance, unsignalized intersection and roundabout with bicycle lane are regarded as the most difficult and dangerous road situations for Level 4 automated vehicles.** When automated vehicles drive on the straight segment of a motorway, they only need to follow the lane markings. However, when they arrive at the exit or they are about to enter this motorway, they need to detect vehicles driving on other lanes and make the decision for following routes, which add difficulties to their driving system. Similarly, automated vehicles should be able to deal with complex situations of unsignalized intersections. Furthermore,

detecting bicycles and pedestrians in the roundabout with bicycle lanes is another challenge for automated vehicles.

Step 3 involves collecting infrastructure requirements and selecting most challenging road situations for automated vehicles from manufacturers and technical researchers. **Step 4** maps infrastructure requirements under most challenging road situations into scenarios and selecting most likely scenarios. These two steps are finished by two rounds of interviews.

The selection of interviewees for two rounds of interviews (Step 3 and Step 4) is based on the expertise of those critical stakeholders. Seven manufacturers and researchers who have experience in testing automated vehicles were interviewees for the first round interview to explore potential requirements. To assess requirements and map them into scenarios, other stakeholders whose specializations include transport planning, traffic management and policy-making were invited to attend the second round interview.

- Future application of Level 4 automated vehicles

All interviewees from the first round hold the positive attitude towards Level 4 automated vehicles, while interviewees from the second round are relatively conservative. Interviewees claim that Level 4 automated vehicles must be able to deal with the mixed traffic situation, otherwise, they will only be allowed to drive in some closed environments but not on public roads. Depending on different predictions, the popularization timeline of Level 4 automated vehicles varies from 2021-2050 to 2023-2058. The procedure of infrastructure upgrades should follow the same timeline.

-Infrastructure requirements

Based on the results of interviews, under Scenario 1 (basic infrastructure), general requirements are: Clear and harmonized lane markings and road signs, Optimal location of (remove) road signs, HD-maps & Road database, National/Global road signs and lane markings gallery and Wireless technology (5G base station, WIFI, Bluetooth). Requirements for specific road situations are: Speed limit signs for unsignalized intersection and motorway exit/entrance, Countdown for traffic signs, Warning signs for vulnerable road users and V2I technology.

Compared with requirements referring to scenario 1, scenario 3 (advanced infrastructure) has five more general requirements: Remove road signs to the road surface, Sensor Readable lane markings, road signs, National/regional clouds and centre, Tailored signs or markings for automated vehicle and Suitable pavement material to deal with new wear pattern, which may need more investment. Dedicated lane with barriers/magnetic transmitter can be an option on motorways. Also, brilliant/different colours can be used to paint the merging conflict of the motorway exit/entrance. Traffic lights in the signalized intersections can be communicated and intelligent with flexible timing. Radar reflectors and camera sensors for specific situations are required for unsignalized intersections. In the roundabout with bicycle lanes, guide marking or road signs for automated vehicle in the roundabout and alert device to inform vulnerable road users are two requirements that do not appear in scenario 1.

Step 5 provides the final results with implementation plans and the stakeholder engagement plan to upgrade infrastructure based on those requirements under most likely scenarios.

- Implementation plan

Figure 1 gives the implementation plan to upgrade infrastructure according to requirements under Scenario 1 (basic infrastructure) and Scenario 3(Advanced infrastructure). Under Scenario 1the whole process for implementing feasible infrastructure requirements will take over forty years, starting from the year 2018 and until the year 2060. Under Scenario 3, the timeline is about ten years' shorter.

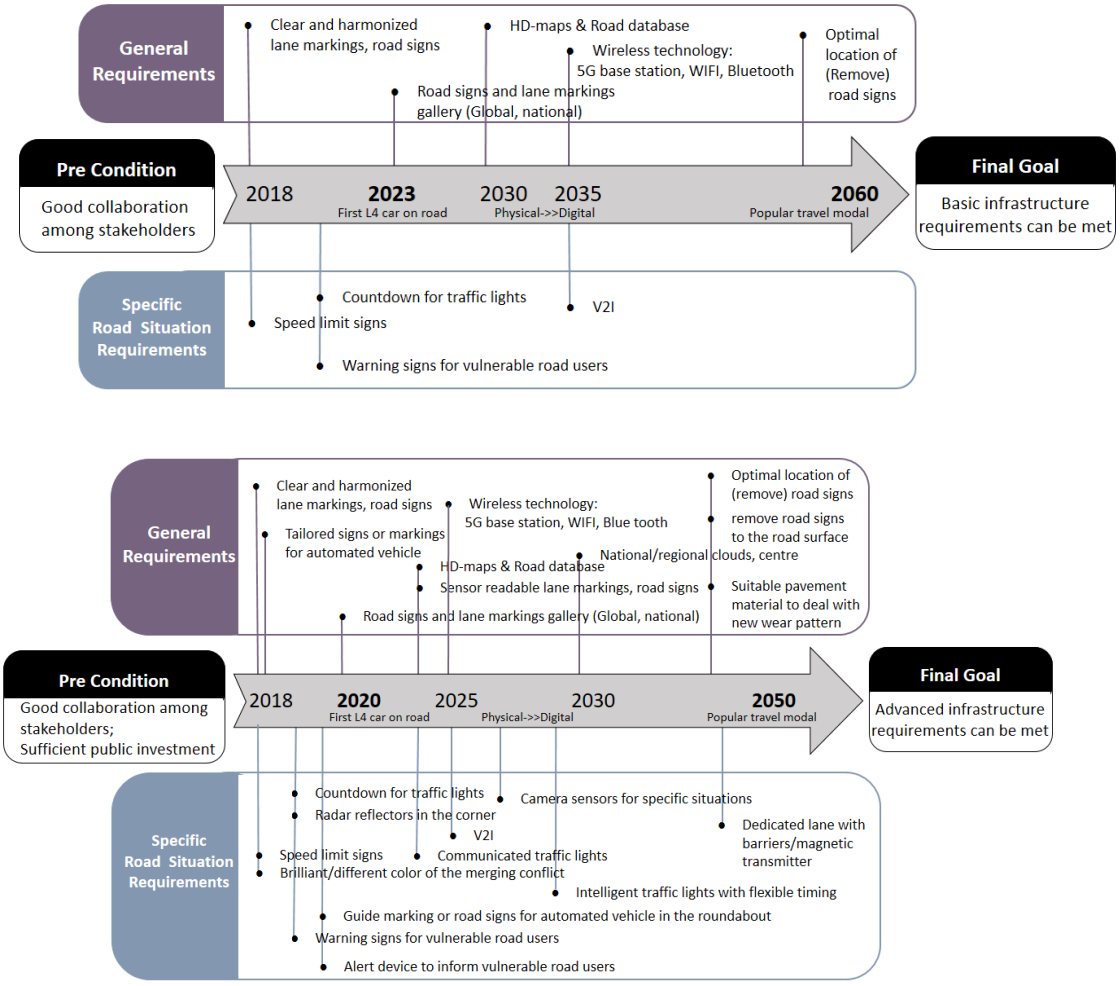

Figure 1 Implementation plans (own illustration)

Figure 2 gives the visualized implementation plans of Scenario 3 in each selected road situation as the example, plans for Scenarios 1 can be found in Chapter 7.

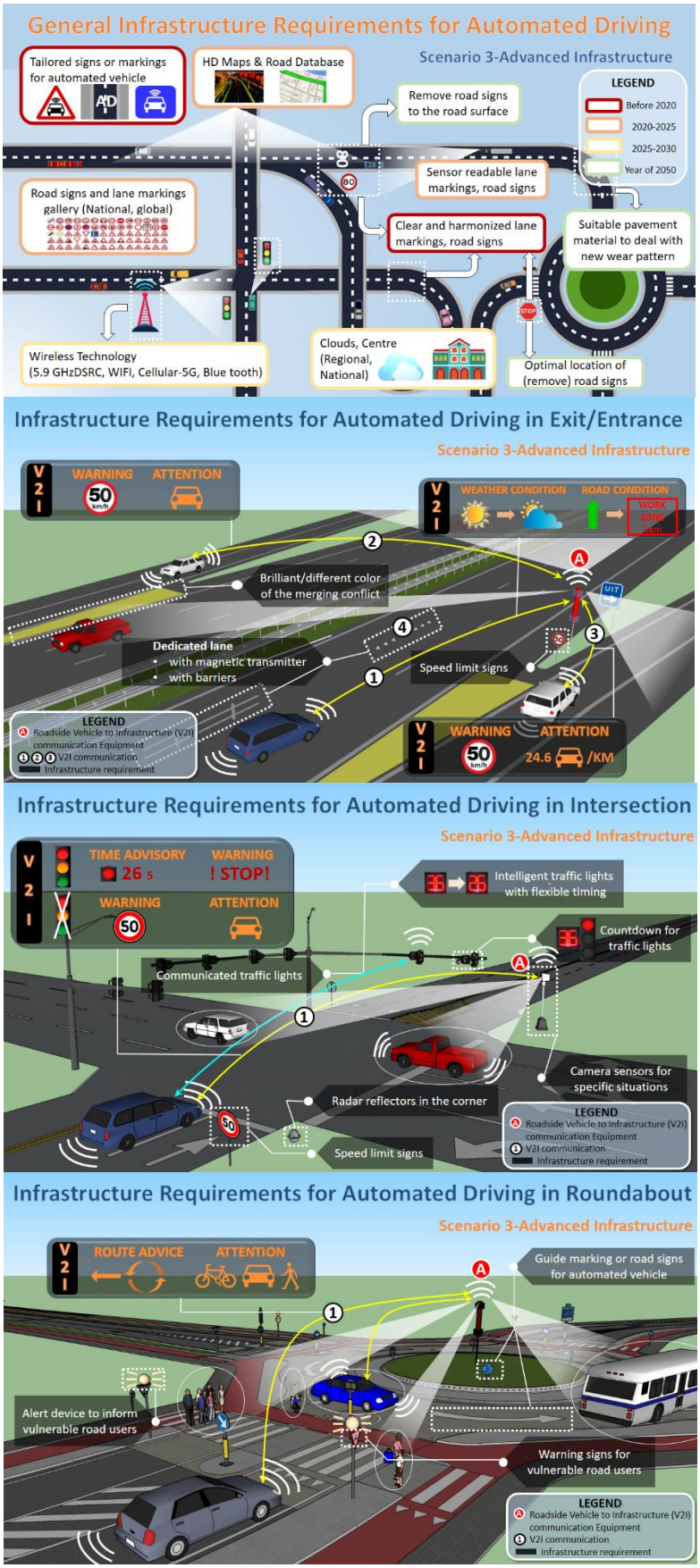

Figure 2 Implementation plan visualization (own illustration)

Conclusion and Recommendations

Two most likely scenarios where the amount of public expenditure and the popularization period of Level 4 automated vehicles differ are applied to describe the future of infrastructure for automated driving. In both Scenario 1 (Basic infrastructure) and Scenario 3 (Advanced infrastructure), clean and harmonized road signs and lane markings, HD-maps and road database and V2I technology are core infrastructure requirements. High-cost requirements, such as intelligent traffic lights, radar reflectors and camera detectors, dedicated lanes and new pavement material can only be achieved in Scenario 3.

The research also finds that the implication of physical infrastructure on automated driving is as important as digital infrastructure and requirements on physical infrastructure are even more than that on digital infrastructure. But a trend of transition from physical infrastructure to digital infrastructure will happen after the first Level 4 automated vehicle is introduced to the market.

The same pre-condition of Scenarios 1 and Scenario 3 is close cooperation among stakeholders. Therefore, only when involved stakeholders are engaged and their concerns' are taken into account, can road authorizes carry out the implementation plan smoothly. This research provides adequate insights to make recommendations to road authorities on achieving this goal based on the stakeholder engagement plan. It is suggested to conduct the Cost-Benefit Analysis (CBA) for each infrastructure requirement solution to make it clear to stakeholders that whether infrastructure upgrading is necessary. Besides, through setting concrete collaboration forms and rules with manufacturers, road authorities can gain more trust of manufacturers. To promote cooperation on upgrading infrastructure, the scope of this cooperation can be expanded with involving more stakeholders who have either powers or knowledge on this issue. Finally, road authorities shall design an open and flexible process to make the decision and hold the international perspective.

The limited scope of this research also leaves room for further researches. Other Levels of automated driving can be further studied and other methods can be applied to the problem. Assumptions could also be further specified. To make the data resource more various, more manufacturers can be selected as interviewees. Another research focus could be linking each infrastructure requirement with the corresponding automated driving technology to study the benefit of each requirement. Estimating the cost of fulfilling those requirements will also be an interesting research.

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List of Abbreviations

AD	Automated Driving
ADS	Automated Driving System
AVs	Automated Vehicles
DDT	Dynamic Driving Task
EU	European Union
HD	High Definition
ODD	Operational Design Domain
SAE	Society of Automotive Engineers
TMC	Traffic Management Centre
V2I	Vehicle to Infrastructure Communication
V2V	Vehicle to Vehicle Communication

Part I
Introduction and Research Design

Chapter 1 Introduction and Research Design

1

Introduction and Research Design

In this chapter, the background of this research and how this research is designed are introduced first, followed by the structure of this report.

1.1 Background of the Research

Automated driving (AD) is propagated as a technology that has the potential to revolutionise transport system in the near future. In the past few years, the research and development of automated driving have made significant leaps in bringing theory into reality (Fagnant & Kockelman, 2015). Two dimensions are often used to describe the development of automated vehicles (AVs), the level of automated driving and the connectivity (Shladover, 2017). As the connectivity of automated vehicles is crucial in bringing additional benefits to the transport system, this research focuses on connected automated vehicles.

According to the taxonomy defined by Society of Automotive Engineers (SAE) (2018) that automated vehicles are classified into five levels, except level 0 that all driving tasks are performed by human drivers. In Level 1 and Level 2 automated vehicles, part or all of the Dynamic Driving Tasks (DDT) can be accomplished by the Automated Driving System (ADS). The remaining levels are Level 3, Level 4 and Level 5 where the ADS performs the entire DDT when engaged. The difference between Level 3 (conditional driving automation) and Level 4 (high driving automation) is whether the human driver is expected to intervene when DDT performance-relevant system fails. For a Level 5 automated vehicle, it is able to drive itself in all driving modes while the Operational Design Domain (ODD) of a Level 4 automated vehicle is limited (e.g. motorways or closed-campus routes).

After the release of Level 1 and Level 2 automated vehicles, many manufacturers are aiming at introducing high-level automated vehicles to the market. The question is no longer whether but when can road vehicles become high-level automated ones. As KPMG and CAR (2012), Google (O'Brien, 2012), Nissan (Nissan, 2013), Tesla (2018), Volvo (2018), and others (Shladover, 2016) claim that high-level automated vehicles probably will be on the streets and highways within the next decade.

The current infrastructure is designed primarily for human drivers. In lower vehicle automation levels (SAE Level 1 and 2), the vehicles are expected to cope with the existing road infrastructures. Since we are moving towards high-level automated vehicles which rely on sensors or Vehicle-to-Infrastructure (V2I)/Vehicle to Vehicle (V2V) communication to recognize the surrounding environment with human drivers either partially or completely unengaged in the driving task, or even with no driver at all, the needs to adapt current infrastructure get higher. Enabling automated vehicles to travel along the public roads may require different infrastructure upgrades or adjustments under different future scenarios.

Therefore, the whole research is carried out with the aim of exploring possible infrastructure requirements under possible future scenarios and then implement these requirements corresponding to the development timeline of level 4 automated driving.

1.2 Problem Definition

Today's road infrastructures are designed to meet the needs of human drivers, which may not be suitable for automated vehicles. The integration of high-level automated vehicles on the current road network is expected to have impacts on traffic efficiency and safety, at the same time, it may also require the upgrades or adjustments of current road infrastructure (CARTRE, 2018). Besides, disengagement reports of automated vehicles tests claim that functionalities of high-level automated vehicles are limited to current road conditions (DMV, 2018). Therefore, whether to upgrade the existing infrastructure and how to do that are becoming a key issue for the deployment of automated driving.

However, although we have realized the importance of cooperative vehicle and infrastructure system, the minimum requirements for the infrastructure for automated vehicles are not yet clearly defined. Vehicle manufacturers prefer to improve the technology of vehicle to cope with the current road infrastructure. For Level 1 and Level 2 automated vehicles, they are capable to be driven on current roads. While when the driving automation level gets higher, physical infrastructure may need adaptation and digital infrastructure shall be applied (e.g. High-Definition maps, V2I communication technology). In addition to that, most of the studies on automated driving are occupied by the technological aspects of automated driving on vehicle level or focus on impacts of automated vehicles. Few researches are available on the infrastructure requirements for automated driving (Nitsche et al., 2014; EU, 2016; Farah et al., 2016; CATAPULT, 2017; Lawson, 2018) and the amount of complete or on-going projects address infrastructure for automated driving is also limited (Vreeswijk, 2018; Harrer, 2018; Lytrivis, 2018). Besides the lack of theoretical and practical reference, how to implement infrastructure requirements in the unpredictable future is also an obstacle for road authorities when they need to make the decision among a set of alternatives. Chapter 2 contains the thorough state-of-art on this research topic.

In consequence, the problem is twofold. The first is that requirements on current road infrastructure for high-level automated driving are unclear (the discussion on which level is chosen for this research is in Section 1.3). Secondly, under which future scenarios shall these requirements be met and how to implement them also remain unknown.

1.3 Research Scope and Research Question

Based on many researchers' predictions, Level 5 automated vehicles will not be on roads before 2075 because of the barriers in legal issues and drivers' psychology issues (Shladover, 2015; SWOV, 2016; TNO, 2016). Level 3 automated vehicles require human drivers' time-to-time attention to response to the request to intervening when necessary (SAE, 2018). This may be problematic due to the difficulty to get drivers' attention after the vehicle is out of control within several seconds (Shladover, 2015; Farah, 2016; SDFE, 2017) and this also means that Level 3 automated vehicles may not require additional infrastructure than manual cars. Besides that, some manufacturers even claim that they will not attempt Level 3. Therefore, this research aims to investigate potential infrastructure requirements for SAE Level 4 automated driving. Both physical and digital infrastructure will be involved, and the research scope includes motorways and provincial roads where may be first allowed for automated vehicles (CROW, 2016).

To address the problem stated in the previous section and the research objective, the following research question is proposed:

What are the road infrastructure requirements to allow for SAE Level 4 automated driving?

Based on the research question and objectives, the corresponding sub-questions are listed below:

Sub-question 1: What are the current research and market status of automated driving and infrastructure?

Sub-question 2: What are the future scenarios regarding infrastructure for automated driving?

Sub-question 3: What are the feasible physical and digital requirements of infrastructure to allow for SAE Level 4 automated driving under most likely scenarios?

Sub-question 4: How to upgrade the road infrastructure under most likely scenarios?

1.4 Research Approach

In order to answer the main research question, the whole research was carried out in five steps based on four sub-questions. Scenarios planning is the main research method to address future uncertainties with literature review and stakeholder analysis to build the research foundation. Two rounds of interviews with manufacturers, road operators and academia institutes were conducted. The first round aimed at collecting potential requirements and the second one was to map requirements into most likely scenarios.

The whole research methodology and approach is illustrated in the following Figure 1.1:

Step 1: Research Background

The first step of the study is to understand the research background of infrastructure and automated driving.

Scientific paper and project reports on the topic of infrastructure and automated driving were reviewed to learn the knowledge gap of this research. Besides the literature study, as a set of stakeholders (e.g. vehicle manufacturers, road authorities, suppliers) are involved in this issue, a stakeholder analysis was conducted to know the market status. With the result of stakeholder analysis, critical stakeholders were selected as interviewees and strategies, harnessing a practical, sustainable solution in the interests of the stakeholders in the long term were come up with.

As a result, a set of theoretical backgrounds are generated and applied in later steps.

The step aims at answering sub-question 1.

Step 2: Scenario Development

The second step of the methodology involves the development of future scenarios regarding automated driving and infrastructure. In order to deal with future uncertainties on the application of Level 4 automated vehicles and stakeholders' attitudes towards upgrading infrastructure for automated driving, scenario planning approach was applied for developing and thinking through possible future states on the basis of different scenarios (Schoemaker, 1995). Scenarios were also the inputs for interviews and were validated by interviewees.

In this step, in addition to building scenarios which describe macro situations, specific road situations where infrastructure requirements may differ was analysed as well to break the whole road network into segments. Those specific road situations made it easier and more concrete for interviewees to understand this research and then give their answers.

This step gives an answer to sub-question 2.

Step 3: Requirements Exploration

After completing Step 1 and 2, requirements exploration is performed. The first round of interviews with seven vehicle manufacturers and researchers who did automated vehicles tests were conducted to explore infrastructure requirements. Specific road situations were used during these interviews to provide interviewees concrete perception of this issue, and they were assessed by interviewees as well. According to the number of interviewees' response to different road situations (whether they give requirements to one situation or not), the most challenging road situations were figured out. They were inputs to design the final implementation plan.

After this step, sub-question 3 can be addressed partly.

Step 4: Requirements Mapping

As requirements are gathered, it is necessary to verify their feasibilities and map them into scenarios.

Requirements collected from Step 3 were used to conduct the second round of interviews with experts from academia, road authorities and other relevant stakeholders whose expertise includes traffic management, transport planning and transport policy. In this step, validation and assessment of scenarios were also finished.

The two rounds of interviews were all transcribed and analysed from the quantitative and the qualitative aspect. To analyse qualitative data, three steps were followed: organizing interview data into categories, labelling those categories, and then finding relationships between the different fragments regarding the main research questions (Chitambo et al., 2016; Boeije, 2005). The software, Atlas.ti, is applied to analyse interview transcripts.

This step gives the final answer to sub-question 3 and provides inputs for Step 5.

Step 5: Plan Development

The final step of this research is to analyse findings and results from each previous step and develop implementation plans of infrastructure upgrades under most likely scenarios.

This step answers sub-question 4.

Research Output

The resulting stage of research is the guidelines and recommendations to upgrade road infrastructure for SAE Level 4 automated driving under different possible future scenarios, including implementation plans, the stakeholder engagement plan and recommendations for road authorities.

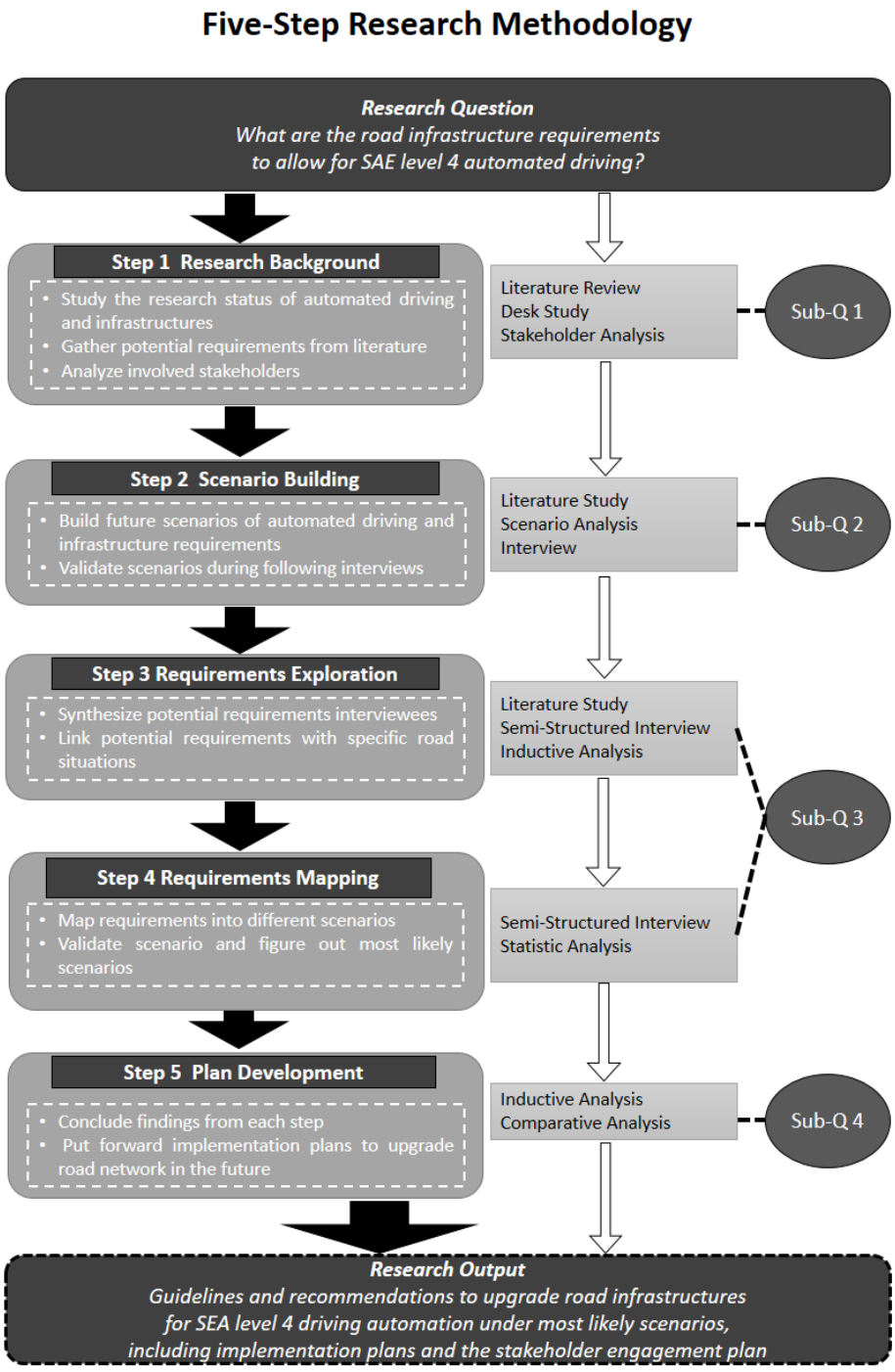

Figure 1. 1 Research Approach

1.5 Structure of the Report

The report is demarcated into four parts and in total nine chapters.

In Part I, Chapter 1 introduces the subject of this research and the design of the research which includes problem definition, the research scope and research questions and the research methods for performing the research project.

Part II concerns the theoretical background of this research. This part starts with the literature review regarding automated driving and infrastructure in chapter 2, with the purpose of investigating what is the current research status. In chapter 3, a Dutch-context stakeholder analysis is performed to figure out critical stakeholders and decide levels of stakeholder involvement to design the stakeholder engagement plan. The application of scenario planning approach is introduced in chapter 4, together with the process to define specific road situations. Part II lays the foundation for performing empirical research in part III.

In Part III, the content shifts from theories to empiricism, in which interview process and results are presented. Chapter 5 is about the first round of interviews to explore infrastructure requirements and select most challenging road situations for automated vehicles. The results of possible infrastructure requirements for Level 4 automated driving in each selected specific road situation under most likely scenarios are in chapter 6. In Chapter 7, two rounds of interview results are compared and combined to develop implementation plans, including roadmaps, the stakeholder engagement plan and recommendations for road authorities.

In the end, the whole report is concluded in Chapter 8, in which sub-questions are solved in turn to answer the main research question. Last but not least, the limitation of this research is clarified as well as recommendations for further research are discussed in Chapter 9.

Part II
Theoretical Background

Chapter 2 Infrastructure and Automated Driving

Chapter 3 Stakeholder Analysis

Chapter 4 Scenario Building

2

Infrastructure and Automated Driving

The aim of this chapter is to address this sub research question '*What is the current research status of automated driving and infrastructure?*' Section 2.1 gives some basic information on automated vehicles. Then, the relation between infrastructure and automated driving is studied and presented in Section 2.2. Section 2.3 presents physical and digital infrastructure requirements for automated driving from scientific literature and projects. In Section 2.4, the literature review is concluded.

2.1 Background of automated vehicles

Over the past decades, the technology of automated vehicles has evolved rapidly due to advances in microprocessors, sensors, geodetic information systems, telecommunications and related technologies (Milakis et al., 2017; Noy et al., 2018). To classify the development of automated vehicles technology, two dimensions are applied: the level of automated driving which defines the extent of human driver involvement in executing dynamic driving task, and the connectivity dimension, varying from 'autonomous' (unconnected) to 'cooperative' (connected) (Milakis et.al, 2017; Shladover, 2018).

The most often used taxonomy that classifies the automated driving levels is defined by the Society of Automotive Engineers (SAE) (See Figure 2.1, SAE, 2018). Five levels reflect the gradual process of vehicle automation, besides Level 0 that the driver performs all driving tasks. Level 1 and Level 2 vehicles require the driver to control the driving system continuously. For Level 3, 4 and 5 vehicle, Automated Driving System (ADS) performs the entire Dynamic Driving Task (DDT) while engaged. The difference between Level 3 and Level 4 automated driving is whether the driver is expected to be available for the occasional takeover of the vehicle or not (SAE, 2018). When an automated vehicle is able to drive in all driving modes which means that its Operational Design Domain (ODD) is unlimited, it will be defined as the Level 5 vehicle.

Level 1 vehicles have already been introduced to the market for several years on a variety of vehicles, while the penetration level is still low. Level 2 systems are installed on some high-end vehicles in recent years, and there is a tendency that more manufacturers will introduce Level 2 systems to their vehicles. Level 3 is problematic based on views of some researchers because of the difficulty to attain drivers' attention after being out of the loop (Shladover, 2015; Farah, 2016; SDFE, 2017). Besides, according to statements from automakers that they will not attempt Level 3 vehicles (GM, 2018; Tesla, 2018; Volvo, 2018). Predictions on the timeline of Level 4 vehicles application vary:

optimistic predictions claim that by 2030, they will be sufficiently convenient and affordable to displace most human-operated vehicles; opponents indicate that there are many obstacles remained before automated vehicles can be allowed to drive, for instance, the need for new infrastructure and regulation system (Johnston & Walker 2017; Keeney, 2017; Arbib & Seba, 2017). Nieuwenhuijsen et al (2018) analyse the long-term innovation diffusion of automated vehicles technology under two scenarios, AV in bloom – conservative and AV in bloom – progressive. In the first scenario, the peak of the market penetration rate of Level 4 automated vehicles is between 2040 and 2050; in the latter scenario, this moment is brought forward to 2030. As to Level 5 vehicles, most of the studies show that they will not be on the road until 2075 (Shladover, 2015; SWOV, 2016; TNO, 2016).

The connectivity dimension is about the distinction between unconnected (autonomous) and connected (cooperative) implementations. If the vehicle performs all the functions by its self-contained system, the automation system of this vehicle will be regarded as 'autonomous.' On the contrary, if the vehicle relies on communications with the infrastructure (V2I) or other vehicles (V2V) to acquire information or to negotiate manoeuvres, the system is 'cooperative' (Shladover. 2017). Figure 2.2 describes the scheme of Autonomous, Cooperative and Automated Systems. In Figure 2.2, the circle representing automated driving systems is biased to the right side because it is increasingly essential for them to be cooperative to produce transportation systems benefits (Shladover. 2017).

In this research, we focus on Level 4 automated driving which will probably be realized within the coming decade and use 'automated driving' to describe the technology where automation of the driving task, vehicle connectivity and the data are brought together.

Level	Name	Narrative definition	DDT		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	OEDR		
Driver performs part or all of the *DDT*						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS ("*System*") performs the entire *DDT* (while engaged)			*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.				
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 2. 1 Automated driving Levels (Source: SAE, 2018)

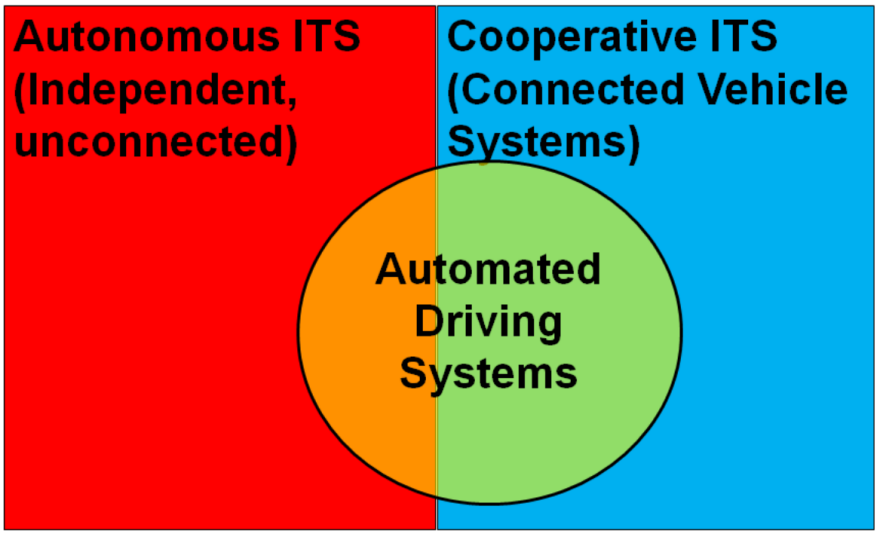

Figure 2. 2 Schematic Depiction of Distinctions Among Autonomous, Cooperative and Automated Systems (Source: Shladover, 2017)

2.2 Infrastructure and automated driving

The results of the literature review on the topic of 'infrastructure' and 'automated driving' are summarized in the two following sections.

2.2.1 Implication of automated driving on infrastructure

The impacts of automated driving on the road infrastructure could be positive or negative based on the practical road and traffic condition (Chen, F et al., 2016).

Many researchers indicated the possibilities of reducing the width of driving lanes, medians, and shoulders. Chen et al. (2016) investigated the potential influences of using automated vehicles on the pavement long-term rutting performance and concluded that the wheel wander distance may be reduced, the lane capacity and traffic speed may be significantly increased. Hayeri et al. (2015) pointed that when all vehicles become automated or connected, the width of lanes, shoulders, clear zones and medians could probably be narrowed due to the lane keeping system of the vehicles. In Somers and Weeratunga's (2015) report, they even indicated that with Level 4 automated vehicles, some safety measures in traditional road infrastructure design (such as wide lanes, shoulders, guardrails, rumble strips) would mostly not be necessary anymore.

Although the precise positioning and accurate steering control of automated vehicles will allow to reduce the lane width or increase the traffic capacity with current road infrastructure, they may change the potential of pavement rutting damage and new wear pattern will appear (Lutin, J. et al., 2013; Carsten, O.& Kulmala, R., 2015). The way to design and the frequency to maintain pavement may thus be changed (Lamb, 2015).

TNO and Royal Haskoning DHV (2016) explored the implication of automated vehicles on road design of motorways and provincial roads, two types of roads that might be first allowed for automated vehicles in the Netherlands (CROW, 2016). They gave recommendations on complete Level 5 and the mix of different Levels. For the mix of vehicles under different Levels, the implication on road design is limited because the human drivers' safe and smooth rides should be ensured. They mentioned the option of separating automated vehicles and conventional vehicles may be needed and highlight the importance of clear road signs and lane markings.

2.2.2 The necessity of infrastructure for automated driving

The introduction of automated vehicles is expected to significantly affect the infrastructure, so it may need to be revolutionized alongside automobiles. Many decision-makers and road authorities have wondered how to plan roads with automated vehicles and whether public policies should encourage or restrict their use (APA 2018; Grush & Niles, 2018; Milakis et al., 2017).

In 2010, the European Commission published a study report named 'Definition of necessary vehicle and infrastructure systems for Automated Driving,' in which the need to create a short- to long-term infrastructure implementation plan was emphasized. The sub-activity 'Facilitating automated driving' of EU (European Union) ITS Platform contained the scope to prepare road authorities to make decisions on facilitating automated driving and automating their own core business (EU,

2016). The Coordination of Automated Road Transport Deployment for Europe (CARTRE, 2017) defined physical and digital infrastructure as one of the challenges for automated driving deployment. Actually, the focus on infrastructure for automated driving is a worldwide issue. KPMG used the quality of infrastructure in a country as a rating indicator to prepare the Autonomous Vehicles Readiness Index (KPMG, 2018). The government of China, Japan and the U.S. also referred the importance of upgrading infrastructure to make automated driving a reality in their official documents (G0V-CN, 2018; The U.S. Department of Transportation, 2017; JAMA, 2018). Nitsche et al. (2014) investigated international experts' attitude towards infrastructure for automated driving and 76% of the respondents considered the role of infrastructure for automated driving as significant.

2.3 Physical and digital infrastructure requirements for automated driving

Nitsche et al. (2014) studied the requirements on the infrastructure for highly automated vehicles based on the results of a literature review and an online questionnaire. They divided those requirements into three aspects regarding different automated driving system groups: the land assistance system, the collision avoidance system and the speed control system. According to this study, clear, consistently placed, and harmonized lane markings and traffic signs, infrastructure-based warning systems for bad weather, roadside V2I/I2V, pedestrian and bicyclist protection and road surface with a sufficient friction coefficient to allow emergency manoeuvres are crucial infrastructure requirements for highly automated driving (Nitsche et al., 2014).

In EU's report 'Identification of requirements towards network authorities,' (2016) requirements towards physical infrastructure and digital infrastructure were introduced respectively. In the section of physical infrastructure, consistency of the quality of road infrastructure for continuity of automated driving is needed. Stricter lane keeping of automated vehicles leads to the requirement that strips where the vehicle wheels run should be equipped with material tolerating wear better. Emergency harbours is also a kind of need in case that malfunctioning automated vehicles or human drivers being unable to regain control in time. For digital infrastructure requirements, communication networks (including WLAN, ITS-G5, 3G/4G and later 5G, internet of things networks ITS-G5 Roadside units, Mobile edge computing, etc.), digital maps, clouds and back office and positioning capability are necessary.

After reviewing numerous literature and projects refer to infrastructure and automated driving, Farah et al. (2016) summarized potential infrastructure requirements to facilitate the vehicle automation. Lane markings, sufficient friction coefficient, traffic signals at intersections in urban areas (vulnerable road users) and current standards for width (lane, shoulder, median, clear zone) are regarded as essential physical infrastructure requirements for Level 4 vehicles, while traffic signs could benefit automated vehicles but are not mandatory. With respect to digital infrastructure, wireless communication beacons and sensors (roadside V2I), cloud-based digital maps and exact positioning of the vehicle receive the attention. They particularly stressed that these findings were concluded from the scientific literature or experts' opinions but not based on empirical data.

The CATAPULT Transport Systems (2017) considered the gap between existing (and planned) infrastructure and the infrastructure required by connected and automated vehicles to proof future

transport systems and networks. According to their work, detailed information and real-time updates are needed when traffic management measures are beginning and ending. Lane markings and signage should be maintained to a high standard in terms of cleanliness, clarity, non-deterioration, non-ambiguous positioning, and non-obscuration. To design appropriate road markings for automated vehicles, the global research project is crucial. Besides, (temporary) safe harbour areas on high-speed roads require appropriate frequency and design. The functionality of service stations and the parking infrastructure also shall be well-designed. Infrastructure mounted sensors and V2I communications could assist automated vehicles when they drive through intersections.

Lawson (2018) analyzed the crash configuration influencers and infrastructure attributes of automated vehicles and gave examples of infrastructure needed for different crash patterns of automated vehicles. Those partners include conventional vehicles, automated vehicles, infrastructure, motorcycles, bicycles and pedestrians. Signing, lining and median barriers are required for almost all crash configuration, except the one with pedestrians. Connectivity with the infrastructure and recognition of other road users are listed as well. To protect vulnerable road users (motorcycles, bicycles and pedestrians), nearside segregation is needed. He put forward a discussion on choosing the best solution for automated vehicles from priority intersections or roundabouts or signals.

There are also some complete or on-going projects addressing infrastructure for automated driving. MAVEN and TransAID focused on I2V applications for cooperative automated driving and traffic management (Vreeswijk, 2018). High Definition (HD) video cameras with detection, traffic sensors with a single entry (cross section related), radar sensors (track related), cloud solutions for infrastructure data and 3D model and HD map of the motorway are added to ASFINAG' road tests (Harrer, 2018). INFRAMIX aims at building a "hybrid" road infrastructure where automated vehicles and conventional vehicles can share the road and space. The physical section of the 'hybrid' road infrastructure includes visual and electronic signalling to inform and guide all vehicles and roadside elements related today Traffic Management Centres (TMCs). In the digital section, highly accurate digital maps, individualized speed and lane recommendations, traffic flow estimation methods for mixed traffic, investigation of different novel traffic management architectures (vehicle-based, cluster of V2Vconnected vehicles, V2I-based traffic control) and combinations, usage of short range (e.g. ITS-G5, WiFi) and long range (cellular) communication and definition of dedicated ITS specific messages are of more importance (Lytrivis, 2018).

As a manufacturer, BMW mentioned the infrastructure in their roadmap to develop automated vehicles. Figure 2.3 gives a view of those requirements which are combined with different Levels of automated vehicles.

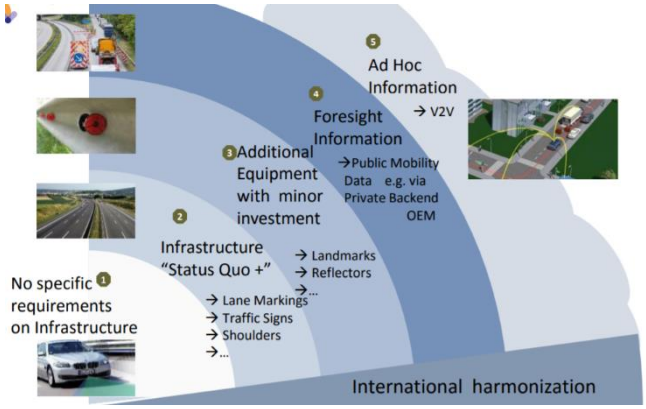

Figure 2. 3 BMW's view on the development of automated vehicles (Wisselmann, 2016)

2.4 Summary

Through the literature review, different levels of vehicle automation and predictions on their future application are explicitly introduced. Although the prediction on the timeline of Level 4 automated driving application is controversial, it is regarded as the most possible automated driving Level that can be achieved. Information helps to understand the background to conduct this research. Then, the distinction between connected vehicles and automated vehicles is explained in detail. Given the advantage in bringing more benefits to the transportation system, connected vehicles receive more attention in this years.

It remains unclear that whether automated vehicles will have positive or negative impacts on the infrastructure. Most researchers pointed out that due to accurate lane keeping functionality of automated vehicles, the width of lanes could be narrowed, which will increase the traffic capacity. Nevertheless, this will also result in pavement rutting damage. Therefore, to design the pavement that allows automated vehicles, we may need to put forward new methods. Besides the requirements on new pavement design methods, researchers, manufacturers and the governments provided some other physical or digital requirements towards automated vehicles. Among those requirements, there are more prominent appearing frequencies for readable lane markings and road signs, roadside V2I/I2V and digital maps. In the short term, good quality and maintenance of physical infrastructure are more important, however, the long-term tendency is that digital infrastructure will replace physical infrastructure gradually before the coming of the high penetration rate of automated vehicles. The necessity of the role that the infrastructure plays in the process of developing and deploying automated vehicles may not be ignored any more.

With the study on infrastructure requirements for automated driving, it is found that most of these requirements come from researchers but not manufacturers who have more practical experience and empirical data on automated vehicles. It is also not yet clear whether infrastructure upgrading is necessary, which requirements shall be met and how to implement those feasible requirements. As the future is always unpredictable and the decision on infrastructure upgrading will be influenced by many factors, the choice of infrastructure upgrading may differ under different future scenarios. As no research give answers and no straightforward method to address these questions, this research

will fill in this knowledge gap. The timeline to apply Level 4 automated driving and the necessity of infrastructure upgrading are designed as interview questions, while requirements exploration and assessment are finished with two rounds of interviews with critical stakeholders.

3
Stakeholder Analysis

In this chapter, stakeholders involved in upgrading infrastructure for automated driving are introduced within the Dutch context. Then, the stakeholder analysis is performed in three distinct levels of detail: stakeholder identification; their interests and level of power, and relations between every two stakeholders. With the results of the stakeholder analysis, a clear view of all actors' positions can be given and strategies to engage them can be determined. A detailed stakeholder engagement plan will be explained in Chapter 7.

3.1 Purpose of Stakeholder Analysis

Stakeholder analysis is important to solve the problem that encompasses or affects numerous people, groups and organizations (Bryson, 2004). For a public organization whose aim is always to satisfy key stakeholders, conducting the stakeholder analysis could benefit the process of strategic management (Bryson, 1995; Moore, 1995).

To research infrastructure requirements for automated driving, first of all, requirements need to be collected from manufacturers or researchers who have relevant knowledge. Then, in order to assess and enhance practical feasibilities of those requirements, more stakeholders need to be involved. Finally, during the implementation phase of infrastructure upgrading, as a public agency, the road authority should put forward measures to satisfy those stakeholders.

Therefore, undertaking the stakeholder analysis could help select suitable interviewees for the following research and design interview questions based on stakeholders' concerns and interests. The conclusion of stakeholder analysis will also be used as the input for the stakeholder engagement plan development. Given the fact that this research is conducted in the Netherlands and most interviewees work for Dutch organizations, this stakeholder analysis represents the Dutch administrative system. In the Netherlands, motorways and some provincial roads are operated by the national road operator, Rijkswaterstaat, and the rest of provincial roads are under the control of provincial governments. To ensure the reference value of this research for other countries, the national road operator is defined as the road authority regardless of local road operators.

3.2 Process of Stakeholder Analysis

The process to undertake a stakeholder analysis contains three steps, starting with stakeholder identification. Firstly, the stakeholders are analyzed on their interests, perceptions of the problem

and goals. Secondly, the power versus interest grid is applied as a tool to help determine stakeholders' status and influences. Thirdly, stakeholder interdependencies will be given to show relations between each stakeholder.

3.2.1 Stakeholder Identification

Eight stakeholders who will affect or be affected by the infrastructure for automated driving are included in the stakeholder identification. Previous workshops on this topic with stakeholders, government publications referring to social impacts of automated driving and similar projects on stakeholder analysis are used as reference to define those stakeholders (CARTRE, 2018; ERTRAC, 2017; EU, 2010; Ministry of Infrastructure and Environment, 2016; The U.S. Department of Transportation., 2017). Those stakeholders are as follows:

- The Ministry of Infrastructure and Water Management: The ministry is in charge of all infrastructure projects nationwide, which consists of three sections: policy, implementation and inspection.

- Road authorities: road authorities are public organizations which execute the Ministry's decisions and are responsible for the design, construction, management and maintenance of the road infrastructure.

- Vehicle authorities: vehicle authorities are public service providers that supervise, register and manage vehicles. In the Netherlands, vehicle authorities are also responsible for the test application if manufacturers want to test their automated vehicles on public roads.

- Manufacturers: manufactures produce and sell automated vehicles.

- Service providers and suppliers: telecom companies, material producers, and other suppliers can make profits during the process of upgrading infrastructure for automated driving. Also, their service or products will either limit or facilitate the implementation of infrastructure requirements.

- Research institutes: they research automated driving from different aspects and provide technical solutions or suggestions to both manufacturers and public agencies.

- Car drivers: they are the consumers of automated vehicles, and their driving habits will be influenced by infrastructure.

- Insurance companies: new insurance policies are needed for automated vehicles. Accidences happen in different road segments may have different imputation of responsibility.

The result of stakeholder identification is listed in Table 3.1.

Table 3. 1 Stakeholder Identification (Dutch context)

Stakeholders	Interests	Problem perception	Goals
The Ministry of Infrastructure and Water Management	Provide citizens with a livable, accessible and secure Netherlands.	Automated vehicles may have impacts on current infrastructure (safety, traffic efficiency) and infrastructure may also influence the deployment of automated driving	Make infrastructure ready for automated vehicles
Road authorities	Maintain and operate roads; meet the Ministry' requirements.	A large amount of potential investment and maintenance cost on infrastructure	Upgrade infrastructure to deal with the generation of automated vehicles
Vehicle authorities	Provide public service for the mobility industry	New rules and regulations to allow automated vehicles be driving on roads are needed	Regulate automated vehicles to provide safe and sustainable mobility
Manufacturers	Design, develop, manufacture, market and sell motor vehicles	Infrastructure may influence the accomplishment of automated vehicles' functionalities; The development of automated vehicles costs time and money	Improve the technology of automated vehicles, promote them and make profits
Service providers and suppliers	Offer service or goods to automated vehicles or infrastructure	Automated vehicles and relevant infrastructure need innovative goods and service	Make their profits in this new industry
Research institutes	Part of the technology supply chain	Provide new paradigms and application solutions	Identify requirements of infrastructure for automated driving
Car drivers	Safe, affordable and comfortable driving experience	High prices; Uncertainty of safety	Benefit from safe and affordable automated driving
Insurance companies	Develop insurance services	It is different to judge the responsible party of an accident caused by automated driving	Make new insurance clauses for automated driving

3.2.2 Power versus interest grid

According to John M. Bryson (2004), the power versus interest grid is applied as a tool to help determine which actors' power and interests must be taken into account and highlight whether to encourage coalitions or not. The matrix has two dimensions, stakeholders' interests in the issue and their power which may influence the achievement of the focal purposes, which leads to four categories of actors: Players (high power and high interest), Subjects (low power and high interest), Context setters (high power and low interest) and Crowd (low power and low interest) (Bryson, 2004).

The Ministry of Infrastructure and Water Management and road authorities are government bodies that have the power to make decisions on upgrading infrastructure or not. Also, their willingness to invest will define which infrastructure requirements can be met. On the other side, providing citizens with safety and reliable infrastructure is their main responsibility. Therefore, they are defined as Players due to their high interest and power level.

Research institutes, car drivers and insurance companies will be influenced if the road infrastructure is changed. However, the extent of the impact is limited and they do not have the power to influence final decisions on infrastructure for automated driving, therefore they are Crowd.

There is a possibility that automated vehicles may only automatically in some specific road situation

within their Operation Design Domain, and functionalities of automated vehicles could be influenced by infrastructure. Therefore, manufacturers' interest in this topic is high. For service providers and suppliers, they can make extra profits if the infrastructure needs to be upgraded. However, both of them do not have high power. They are Subjects.

As a public agency, the power of vehicle authorities is high while infrastructure is not their focus. So vehicle authorities are context setters.

The result is shown in Figure 3.1.

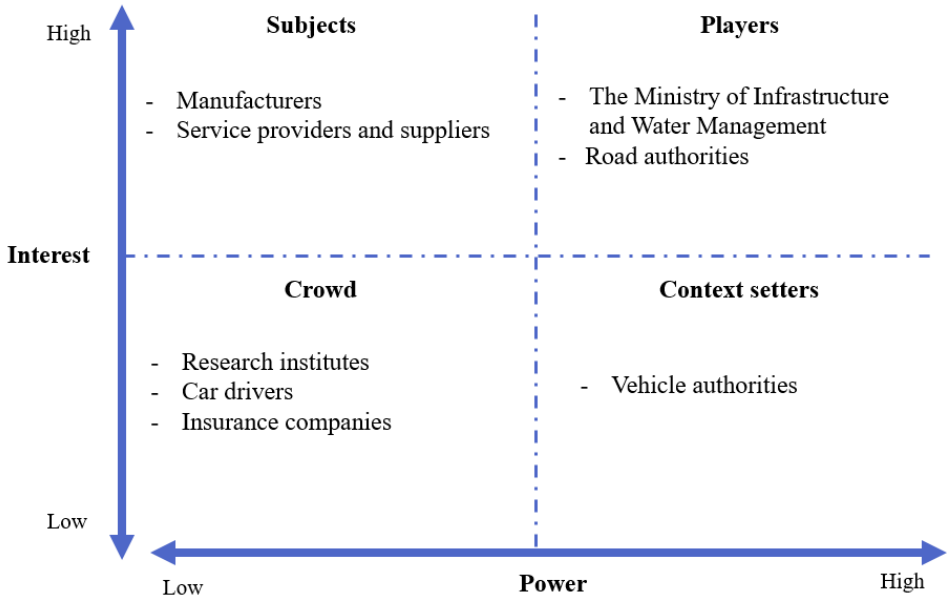

Figure 3. 1 Power versus interest grid

3.2.3 Stakeholder Interdependencies

After the analysis of interests and power of involved stakeholders, resources that each stakeholder possesses are also key factors that must be considered, which help to understand the interdependency between two stakeholders and develop strategic action plans to fulfil their purpose successfully. Analysis of resource is shown in Table 3.2. To help illustrate the resources, characteristics of replaceability and dependency are described. Resource dependency is determined on the level of importance and replaceability of resources. Finally, whether the stakeholders are critical actors is identified based on the previous analysis.

Table 3. 2 Resource dependency and critical actors

Stakeholders	Important Resources	Replaceability (low/moderate /high)	Dependency (low/moderate /high)	Dependency Relationship	Critical actor
The Ministry of Infrastructure and Water Management	Authorities on investment and policy	Low	High	Road authorities; Vehicle authorities	Yes
Road authorities	Knowledge and authority on road infrastructure maintenance and construction	Low	High	Research institutes; Service providers and suppliers	Yes
Vehicle authorities	Knowledge and authority on vehicle supervision, registration and test application	Low	High	Manufacturers	Yes
Manufacturers	Knowledge on automated vehicles technology; experience on road tests	Low	High	Service providers and suppliers; Vehicle authorities	Yes
Service providers and suppliers	Knowledge on their products and services	Low	High	Vehicle authorities; Manufacturers	Yes
Research institutes	Knowledge on both automated driving and infrastructure; help manufacturers to do vehicle tests; Collaboration with a lot of organizations	Moderate	High	Vehicle authorities; Manufacturers	Yes
Car drivers	Driving experience; Willingness to possess services or products	High	Moderate	Insurance companies; Manufacturers	No
Insurance companies	Knowledge on responsibility affirmation in traffic accident	Moderate	Low		No

The interdependencies of those stakeholders are visualized in Figure 3.2.

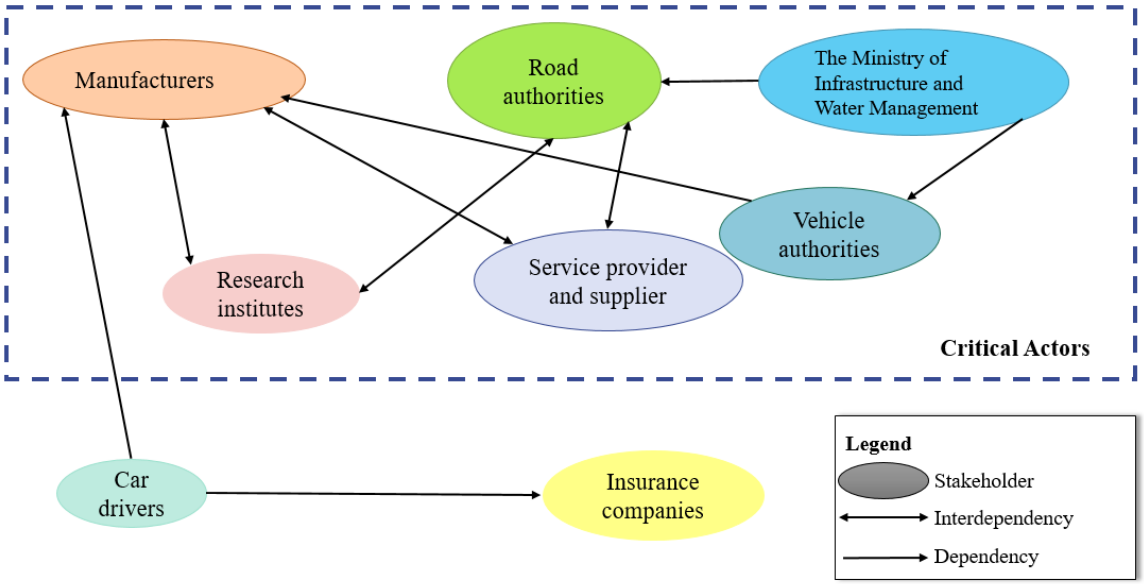

Figure 3. 2 Stakeholder interdependencies

3.2.4 Stakeholder Engagement Strategy

With the analysis results from former sections, strategies to engage stakeholders can be set. In this research, the five levels of stakeholder involvement described by Byson (2004) is undertaken to design strategies (See Table 3.3):

Table 3. 3 Levels of stakeholder involvement (Byson, 2004)

Level of Involvement	Description
Inform	We will keep you informed
Consult	We will keep you informed, listen to you, and provide feedback on how your input influenced the decision
Involve	We will work with you to ensure your concerns are considered and reflected in the alternatives considered, and provide feedback on how your input influenced the decision
Collaborate	We will incorporate your advice and recommendations to the maximum extent possible
Empower	We will implement what you decide

The involvement of each stakeholder in this research is listed in Table 3.4 based on their positions and interdependencies. This table will be used to make the stakeholder engagement plan in Chapter 8.

Table 3. 4 Stakeholder involvement Level

Stakeholders	Level of Involvement
The Ministry of Infrastructure and Water Management	Empower
Road authorities	Collaborate
Vehicle authorities	Consult
Manufacturers	Collaborate/Involve
Service providers and suppliers	Involve
Research institutes	Consult
Car drivers	Inform
Insurance companies	Inform

3.3 Summary

It can be concluded that critical actors are: The Ministry of Infrastructure and Water Management, Road authorities, Vehicle authorities, Manufacturers, Service providers and suppliers and Research Institutes. Accordingly, the involvement levels of these stakeholders are higher than the other two non-critical actors.

Among critical actors, manufacturers and research institutes will be the suitable interviewees to explore requirements as they have experience in automated vehicle tests. Other critical stakeholders' expertise could be used to help assess those requirements and map them into scenarios.

To design interview protocols, stakeholders' knowledge areas and important resources must be taken into account. The semi-structured interview can be considered as the interview type which allows new ideas to be brought into during the interview based on answers from interviewees.

It can also be learned from this chapter that different stakeholders have different core values and concerns. The process to upgrade infrastructure for automated driving must be open and flexible to satisfy most of them. Only in this way can the process proceed smoothly and achieve the goals. The stakeholder engagement plan is as important as the implementation plan.

4

Scenario Building and Road Situation Definition

The future is always unknown, but we can explore the possibilities and do the planning. In this chapter, the scenario planning approach is performed to build future scenarios in terms of infrastructure and automated driving, beginning with a short introduction to scenario and scenario planning. Then, the four scenarios used in this research are illustrated which answer the second sub research question '*What are the future scenarios regarding infrastructure for automated driving?*' As scenarios always provide macro descriptions, specific road situations where requirements on infrastructure for automated driving may differ are studied. They are regarded as concrete situations under scenarios.

4.1 The Introduction to Scenarios and Scenario Planning

Scenarios are not predictions for the future nor are the strategies to deal with the future situation. Instead, they are hypotheses that describe a range of possibilities for the future with imaginative narratives (Shell, 2008; Ogilvy & Schwartz, 2004). A set of scenarios can be regarded as rich, data-driven stories about tomorrow and together form an organizing framework that can be used to make sense of conflicting or ambiguous market signals more holistically (GBN, 2007).

Scenario planning is a method for developing and thinking through possible future states on the basis of different scenarios (Schoemaker, 1995). Instead of assessing or arguing what will the future situation be and how should we face the unknowns, scenario planning provides decision makers with 'what if' alternatives. The focus switches from finding out the most likely outcome to considering implications of uncertainties and making preparations for upcoming changes.

Since the introduction of scenario planning, several approaches are developed for fitting different application aims and under different application circumstances (Bishop, Hines & Collins, 2007). Also, those approaches provide various processes to develop scenarios. Although these processes differ in their details, they have some similar and core steps. Schwartz (1991) describes an approach to development scenarios step by step in his book: The Art of the Long View, which is widely used by researchers and companies (See Appendix A). This research will follow the logic of Peter Schwartz's methodology to construct scenarios.

4.2 Steps to build scenarios

Considering that Schwartz's (1991) methodology is designed for analysing specific business issues while this research subject is a public issue, some steps will be skipped to simplify the process, but the sequence remains the same.

First of all, the focus is defined as infrastructure for automated driving. Then, based on the results of a literature review, key factors and driving forces are identified. After that, the impacts and uncertainties of the driving forces are assessed to figure out the top two driving forces, which are used to construct the scenario matrix. Finally, these scenarios are validated during interviews with experts.

The detailed steps undertaken in this research are in Appendix A.

4.3 Scenarios

Four scenarios are constructed assuming combinations of high or low expenditure and close or loose cooperation among stakeholders involved in infrastructure for automated vehicles (see Figure 4.1)

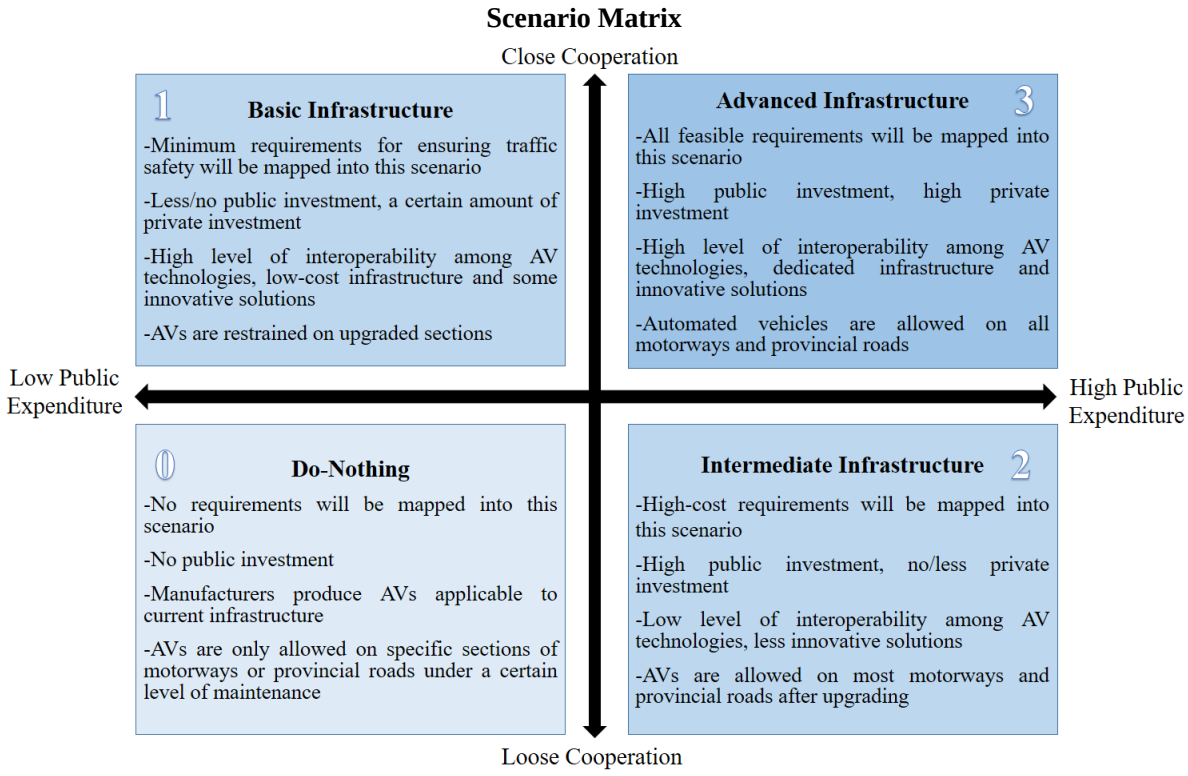

Figure 4. 1 Scenario Matrix

4.2.1 Scenario 0: Do-Nothing Scenario

Scenario 0 is the most negative scenario where stakeholders refuse cooperation and the public expenditure approaches zero.

The ministry doubts the benefits of automated driving, so they reject to upgrade infrastructure for automated driving. None of the manufacturers' requirements will be mapped into this scenario. All they can do is to improve the technology of their vehicles' driving system and make their products applicable to current infrastructure.

Under this scenario, the development and deployment of automated driving will be slow down. Level 4 automated vehicles can only be allowed on specific sections of the road network, for instance, the straight segment of the motorway.

4.2.2 Scenario 1: Basic Infrastructure Scenario

In Scenario 1, stakeholders work closely and are willing to share their knowledge. It is called basic infrastructure scenario where minimum requirements for ensuring traffic safety can be met.

Although public investment is insufficient, there might be a certain amount of private investment. Stakeholders are aware of the importance of infrastructure for automated driving. A variety of cooperation forms and projects have emerged which output several innovative solutions to upgrade the road infrastructure.

Under Scenario 1, the Operational Design Domain of Level 4 automated vehicles can be expanded. They are allowed to be driving on road sections where the infrastructure has already been upgraded.

4.2.3 Scenario 2: Intermediate Infrastructure Scenario

Scenario 2 describes such a situation that the government holds the positive attitude towards automated driving and the public expenditure is sufficient. However, in the increasingly competitive environment, stakeholders refuse cooperation.

Under this circumstance, the road authority could improve the quality of current infrastructure or install more roadside facilities which are already available at the market. They hope to promote collaboration by adding more public investment and making the road infrastructure more suitable for automated vehicles.

Therefore, those high-cost requirements but can be met with existing technology will be mapped into this scenario. With a vast amount of investment, the road authority aims at opening most motorways and provincial roads for Level 4 vehicles.

4.2.4 Scenario 3: Advanced Infrastructure Scenario

Scenario 3 is the most optimistic where all requirements can be transferred into the reality as long as they are reasonable and feasible.

Not only has the public investment arrived at a high Level, but also private sectors show their investment intent. In addition to collaboration between public parties and private parties, different manufacturers also work together to promote interoperability among automated vehicles technologies. Dedicated infrastructure could also be an option for promoting people's Level of

acceptance of automated driving.

After the completion of upgrading motorways and provincial roads, Level 4 automated vehicles should be able to be driving on the whole network, which advances the benefits of automated driving in enhancing road safety and improving traffic efficiency.

4.4 Specific Road Situation Definition

In this research, specific road situations are defined, where the impact of infrastructure on automated vehicles may differ. Consequently, requirements on the infrastructure will be different as well.

Four main kinds of resources are utilized to partition road situations:

- Components of the road network

In guide manuals for motorways, straight segment, curve segment and easement curve segment have different requirements for the geometry design (RWS, 2017; Ministry of Transport, 2006). When compared with the motorway system, intersections and roundabouts are two components of provincial roads.

- Studies on road design and automated driving

In the report 'Zelfrijdende auto's Verkenning van implicaties op het ontwerp van wegen' written by TNO and Royal Haskoning DHV (2016), in order to study the implication of self-driving cars on road design, they choose the following design elements as the focuses: straight road, weaving area, on/off ramp, intersection and roundabout.

- Disengagement report of automated vehicle road test (See Appendix B)

The result of autonomous vehicles' disengagement reports shows that most accidents happen at the intersections (both signalized and unsignalized). Among the external causes, poor lane markings, construction zones and unpredictable pedestrians are three main reasons (Favarò et al., 2018). The elaborate analyze result can be found in Appendix B.

- The environment perception technology of automated vehicles (See Appendix C)

In response to the dynamic driving environment, the automated vehicle needs to collect information comes from the infrastructure, make a decision based on the information, and then execute that decision. This sense-plan-act process will be influenced by different road situations.

The straight and curve segment of the motorway are the two simplest situations as the vehicle only need to follow the guide of lane markings. However, when driving to the exit and entrance, vehicles should be able to make the right decisions. In the weaving area, it is necessary that automated vehicles can sense vehicles coming from the other direction. In provincial roads, intersections and roundabout are situations that challenge automated vehicle's sensor technology. Considering the impact of human factors and the Dutch context, the roundabout with bicycle lanes should be separated from conventional roundabouts.

To conclude, four segments which represent typical motorway situations and four segments regarding provincial roads make up the specific road situations. They are: motorway-straight segment, curve segment, weaving area and exit/entrance; provincial road-unsignalized intersection, signalized intersection, roundabout and roundabout with bicycle lane. Figure 4.2 gives an overview of them.

Figure 4. 2 Specific road situations (Source: Google map)

4.5 Summary

In this chapter, first, the scenario planning approach is performed to construct scenarios. Two main driving forces, public expenditure and cooperation, are applied to build the scenario matrix, which contains four possible future scenarios (Do-nothing Scenario, Basic Scenario, Intermediate Scenario and Advanced Scenario). These scenarios still need to be validated through interviews aim at assessing requirements.

Eight specific road situations of the motorway and the provincial road will be beneficial for specifying the research content and making the research topic more concrete. Their application will be reflected in interviews to explore infrastructure requirements.

Part III
Empirical Research

Chapter 5 Requirements Exploration

Chapter 6 Requirements Assessment

Chapter 7 Plan Development

5

Requirements Exploration

This chapter explains the procedure to collect infrastructure requirements for automated driving through interviews with manufacturers and researchers, as well as the results (the first round of interviews). It starts with the interview set-up, selection of interviewees and the process to conduct interviews. Subsequently, the transcription of each interview is analyzed from the perspective of qualitative data and descriptive data. Findings are presented in the final section and are used as inputs for later research steps.

5.1 Data Collection

5.1.1 Set-up of Interview

The whole interview is divided into two sections.

The first section contains four semi-open questions. The idea is to get interviewees' attitudes towards Level 4 automated vehicles and perceptions of the necessity to upgrade infrastructure. In order to design the future plan to implement infrastructure requirements, their predictions on the timeline of Level 4 vehicles' application and their experiences on trails are gathered as well.

Another section is a survey whose purpose is to collect interviewees' responses to road situations. Eight specific road situations are demonstrated in the form of pictures. Interviewees can write down their requirements of the infrastructure for each scenario or leave no-requirement response which means that they think Level 4 automated vehicles can cope with the current infrastructure. Whether one scenario receive requirements and the priority of those requirements will be gathered and analysed.

An interview protocol can be found in Appendix D.

5.1.2 Interviewees Selection

With the aim of acquiring sufficient empirical knowledge on infrastructure requirements for automated driving, interview candidates are selected based on their experience and expertise with regard to developing automated vehicles or testing those vehicles on public roads. As such, manufacturers could be suitable interviewee candidates. However, given the research results of Chapter 2 and 3 that, manufacturers might not be willing to cooperate under some circumstances,

researchers who ever worked in manufacturing companies or have joint projects with manufacturers could also be selected.

To ensure the diversity in the responses, the nationality and background of the interviewees are also taken into account. Finally, seven professionals from China, Germany, the Netherlands and the U.S were invited to attend the interview. Three of them now work as manufacturers, which are General Motor, Bayerische Motoren Werke and Uber. The rest are researchers who specialize in automated vehicles.

The details about the interviewees are listed in Table 5.1.

Table 5. 1 List of interviewees (First round)

Interviewee	Work/Research experience on AD	Expertise	Organization type	Organization
#1 	6 years	Programming algorithm of automated vehicles	Manufacturer	General Motor
#2 	8 years	Human factors in automated driving	Research institution	Delft University of Technology
#3 	3 years	Traffic management	Research institution	Harbin Institute of Technology
#4 	9 years	Traffic safety	Research institution	Netherlands Organisation for applied scientific research-TNO
#5 	2.5 years	Driver's behavior	Manufacturer	Bayerische Motoren Werke
#6 	5 years	Environment perception of automated vehicles	Manufacturer /Research institution	University of California, Berkeley
#7 	10 years	Connected and automated driving	Research institution	Netherlands Organisation for applied scientific research-TNO

5.1.3 Conducting the Interview

The semi-structured interview was performed as the interview method to collect data. An interview protocol was organized before conducting the interview, which contains the interview aim that has already been introduced in Section 5.1.1. For each interviewee, an email named 'Invitation for an interview' which gives a short description of the research and the interview was sent before the interview. Based on different backgrounds of them, the interview questions were slightly adjusted. Interviews with experts who live in the Netherlands were conducted face-to-face, while for those who live outside the Netherlands, the video interview was adopted. Those conversations were recorded by using audio-tape after getting permits from interviewees.

After finishing the interview, the conversation was transformed into interview transcripts and the recording was deleted. Subsequently, interview transcripts were analyzed with the assistance of two kinds of software, Excel and Atlas.ti. The process and results of data analysis are presented in the next section.

5.2 Data Analysis

Saunders-Smit (2017) summarized two types of data collection:

- Qualitative data: data collected by means of observation of the environment of interest such as texts, photos and people
- Quantitative data: numerical results of measured or simulated variables from surveys, experiments, etc.

Given the goals of conducting interviews and the formulation of interview questions, both qualitative and quantitative data are collected.

5.2.1 Descriptive Data Analysis

Quantitative methods emphasize objective measurements and the descriptive analysis of data to explain a particular phenomenon (Babbie, 2010). According to the interview questions and answers from interviewees, in this research, quantitative data is concluded in the following aspects:

- Timeline and attitude towards Level 4 automated driving

All of the interviewees held positive attitudes towards Level 4 automated vehicles, but their predictions on the timeline were various (See Table 5.2). Based on their predictions, the first Level 4 vehicle will be most probably introduced to the market in 2021, which is five years later. Between 2040 and 2060, they are likely to become a popular travel modal for normal citizens. How long will the promotion process take is influenced by many factors, for instance, people's acceptance of new technology, the robustness of the technology, policies, permits on more tests, the government's attitude, the global economy and so on.

Table 5. 2 Interview results of Timeline and attitude towards Level 4 automated driving (First round)

First round interview result of Level 4 automated vehicles' future application

Interviewee	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**AVE**
Attitude towards the future of L4	P*	P	P	P	P	P	P	**100% P**
Market entry time (year)	2023	2020	2023	2023	2021	2020	2023	**2021**
Become a popular travel modal(year)	2050	2040	2060	2060	2040	2050	2050	**2050**

* P=Positive Attitude

- Conditions of Level 4 automated driving

Figure 5.1 gives the interview results of conditions of Level 4 automated driving, which contains two parts, whether Level 4 automated vehicles can be driving in mixed traffic and whether dedicated lanes are requisite.

First round interview result of Level 4 automated vehicles' driving condition

Interviewee	#1	#2	#3	#4	#5	#6	#7
In mixed traffic	Y*	Y	N	Y	Y	N	Y
Support dedicated lane	N*	N	Y	N	N	Y	N

* Y=Yes N=No

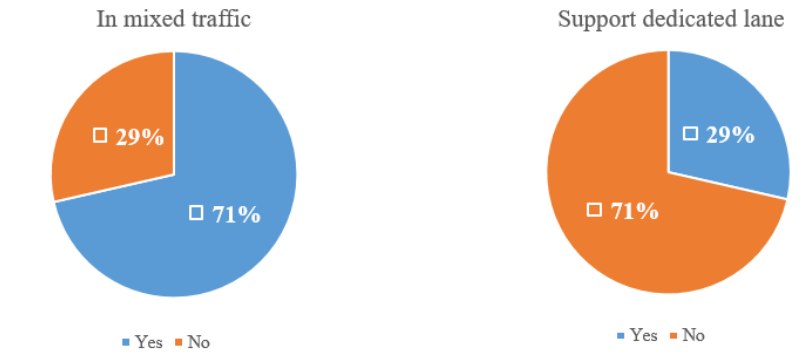

Figure 5. 1 Interview results of conditions of Level 4 automated driving (First round)

When asked whether Level 4 vehicles can be driving in mixed traffic, five interviewees said 'yes.' They thought that mixed traffic is the situation that must be dealt with by Level 4 vehicles if they need people's acceptance. However, the other two interviewees argued that only when all vehicles are connected, can Level 4 vehicles be allowed to be driving on public roads. With current sensor technology, it is impossible for Level 4 automated vehicles to detect all conventional cars around them, which will put a threat on traffic safety. Interviewees who claimed that mixed traffic is an unrealistic situation for automated vehicles also support dedicated lanes. On the contrary, dedicated lanes are unnecessary if Level 4 vehicles are able to cope with conventional cars. Actually, many interviewees used the word 'impossible' to describe dedicated lanes and the main reason is the lack of investment and space.

- Change of infrastructure for test

It can be learned from Figure 5.2 that most of the interviewees did not change the infrastructure when testing the automated vehicles on public roads. The goal of their tests was to improve the technology of their automated vehicles for ensuring that those vehicles are capable to be driven with current road infrastructure. Only one interviewee reported that a change of the infrastructure during his test of automated vehicles. He said that traffic lights and a roadside camera detector were added to an unsignalized intersection. Another expert chose the route where ITS-G5 and HD-maps are available to conduct tests, which he perceived as infrastructure change.

First round interview result of change of infrastructure for tests

Interviewee	#1	#2	#3	#4	#5	#6	#7
Change of infrastructure for tests	N	Y	N	N	N	N	Y

* Y=Yes N=No

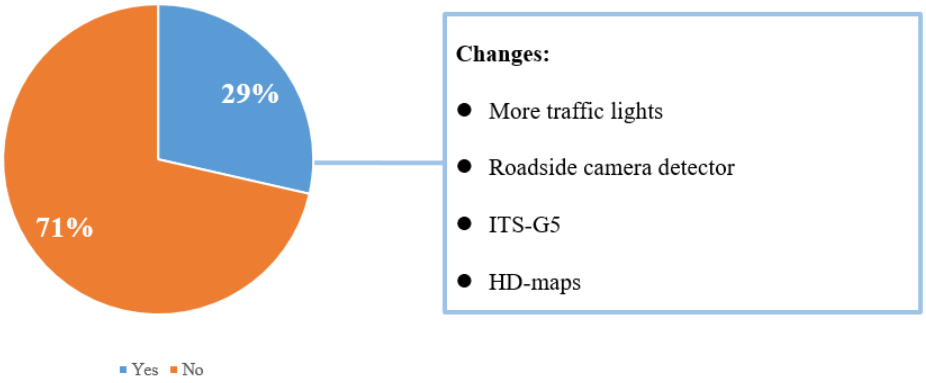

Figure 5. 2 Interview results of the change of infrastructure for test

- The necessity of infrastructure upgrades

Figure 5.3 shows the results of interviewees' opinions on the necessity of infrastructure upgrades. Over half of the interviewees affirmed the necessity while one of them denies it. The reason why two people give the in-between answer is that it depends on the government's willingness to invest.

First round interview result of the necessity of infrastructure upgrades

Interviewee	#1	#2	#3	#4	#5	#6	#7
Infrastructure upgrades	Ne	Be	Ne	Ne	Be	Ne	Un

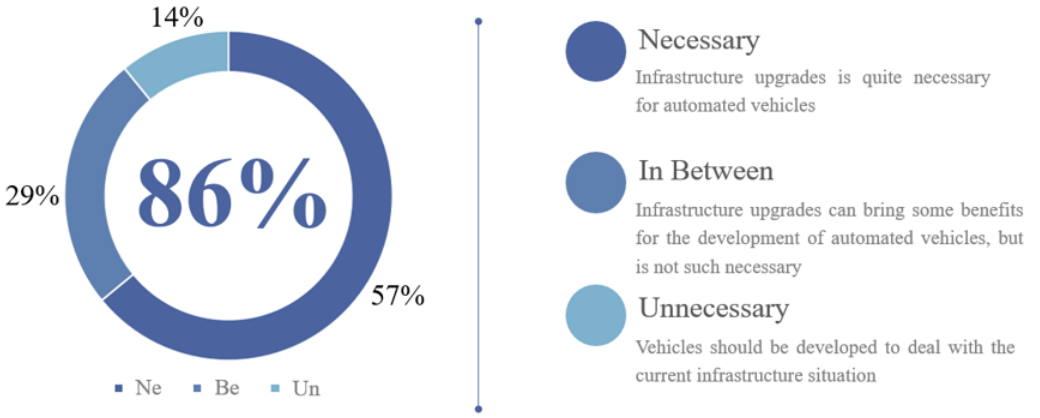

Figure 5. 3 Interview results of the necessity of infrastructure upgrades (First round)

- The response to road situations

Interviewees could choose to write down the possible infrastructure requirements under each specific road situation or leave the blank. The total responses of each road situation are illustrated in Figure 5.4. Straight segment of motorway receives the least response while roundabout with bicycle lane and signalized intersection receive everyone's response.

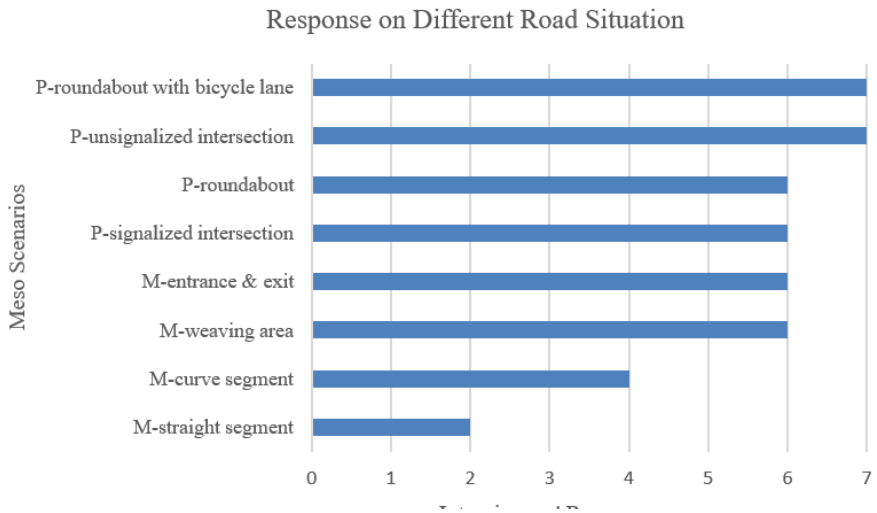

Figure 5. 4 Interview results of the response of specific road situations

5.2.2 Qualitative Data Analysis

There are three stages to resume qualitative data: organizing interview data into categories, labelling those categories, and then finding relationships between the different fragments regarding the main research questions (Boeije, 2005). With the help of the software-Atlas.ti, all interview transcripts are coded through three steps: open coding, axial coding and selective coding.

Firstly, each interview transcript was read a second time and every piece of interesting information was coded into categories. After open coding, the code system was established with either removing or merging some categories and the process was repeated multiple times. This is the axial coding. Finally, the selective coding was performed. Some categories were selected as core categories to form a pattern that displays the findings of the interviews in the best way.

The detailed coding process can be found in Appendix E. After finishing the whole coding process, qualitative data is summarized in the following aspects:

- Influence factors for infrastructure upgrades

Table 5.3 lists the keywords of influence factors for infrastructure upgrades that are mentioned during the interviews. They are divided into three categories according to the frequencies of their appearance in seven interview transcripts.

Based on answers of interviewees, in different regions, the decision on whether to upgrade infrastructure and which kind of infrastructure need upgrades will be different as well. They also put forward the 'chicken and egg' question: shall we first allow the introduction of Level 4 vehicles to the public roads or shall we finish the infrastructure upgrades first. Besides, they figured out the importance of private investment in this issue as infrastructure upgrades always need a large amount of investment which the government may not be able to afford.

Table 5. 3 Interview results of influence factors for infrastructure upgrades (First round)

Influence factors for infrastructure upgrades			
High Frequency (>4)	**Moderate frequency (>2)**	**Low Frequency (1)**	
Regional difference	Collaboration	Target audience difference	Equity
'Chicken and egg' question	Result of cost benefit analysis	Road capacity	Market entry time
Private investment	Policy support	Government encourage	Top-down management
	Public investment	Economic development	Current travel modal preference
	More test permit	Age group difference	Drivers' behavior
		The reliability of technology	Market needs
		Cultural difference	Functional safety

- Manufactures' concern on infrastructure for automated driving

Most of the interviewees emphasized the needs for more tests. Only with numerous test results and data, can we know how to upgrade the infrastructure for automated driving and the applicability of each infrastructure solution. They also pointed out the interdependency and joint development between car sharing and automated driving. As many stakeholders will be involved in the process of infrastructure upgrades, they were worried about whether the relation between competition and collaboration can be balanced well. In addition to these three core concerns, other concerns are listed in Table 5.4.

Table 5. 4 Interview results of Manufacturers' concerns on infrastructure for automated driving

Manufacturers' concerns on infrastructure for automated driving			
High Frequency (>4)	**Moderate frequency (>2)**	**Low Frequency (1)**	
Requirement for test	Process of upgrading	Front-end management	Traffic efficiency
Car sharing	New maintain strategy	Mutual operation	Change of infrastructure
Competition and collaboration	'Win-win' situation	Recommendation to road authority	Traffic congestion
The importance of safety		Private public partnership	Stakeholder engagement
		Less infrastructure	Cultural difference

- Physical and digital requirements

Both the answers to open questions and the survey are regarded as resources to explore interviewees' requirements on infrastructure for automated driving.

To in line with results from the literature review and make the analysis clear, two main categories are used to classify those requirements, physical requirements and digital requirements. In the physical infrastructure requirements category, specialized lanes, lane markings & road signs, traffic lights, vulnerable road user & unconnected vehicle protection and pavement are set as the subcategories. In the digital category, subcategories are maps, sensors, traffic data centre & clouds, vehicle-to-infrastructure communication (V2I). Table 5.5 and 5.6 give the overview of all requirements.

Table 5. 5 List of physical infrastructure requirements based on the first round of interviews

Physical--Infrastructure Requirements		
Specialized lanes	Dedicated lane with barriers	Motorway-general
	Dedicated lane with magnetic transmitter	Motorway-general
	An extra straight lane to cross the roundabout	Roundabout
	Rescue lane for broken down AVs	Motorway-general
Lane markings & Road signs	Clear and harmonized lane markings, road signs	General
	Sensor readable lane markings, road signs	General
	Tailored signs or markings for automated vehicle	General
	Loop signs in the curve segment of motorway	General
	Brilliant/different color of the merging conflict	Motorway-Weaving area/ Exit & Entrance
	Speed limit signs for intersections, entrances and exits of motorways	Motorway-Exit & Entrance Intersection-general
	Guide marking or road signs for automated vehicle in the roundabout	Roundabout
	Warning signs for Vulnerable road users	Roundabout with bicycle lane
	Remove road signs to the road surface	General
	Optimal location of road signs	General
Traffic lights	Good design of traffic signal timing	Signalized intersection
	More visible (bigger) traffic lights	Signalized intersection
	Countdown for traffic lights	Signalized intersection
	Communicated traffic lights	Signalized intersection
	Intelligent traffic lights with flexible timing	Signalized intersection
Vulnerable road users and unconnected vehicles protection	Alert device to inform VRUs	Roundabout with bicycle lane
	Isolating facilities	Roundabout with bicycle lane
	Concave mirror and convex mirror at the unsignalized intersection	Unsignalized intersection
Pavement	Suitable pavement material to deal with new wear pattern	General

Table 5. 6 List of digital infrastructure requirements based on the first round of interviews

Digital–Infrastructure Requirements		
Map	HD-maps	General
	Road database	General
	Global road signs and lane markings gallery	General
	National road signs and lane markings gallery	General
Sensors	Camera sensors for specific situations	Unsignalized intersection
	Radar reflectors in the corner	Intersection-general
Traffic control/ data center, clouds	National center, clouds	General
	Regional center, clouds	General
	Global clouds	General
I2V/V2I	Straight segment: weather condition and road condition broadcast	Motorway-Straight segment
	Curve segment: speed warning and vehicle detection	Motorway-Curve segment
	Weaving area: speed warning and vehicle detection	Motorway-Weaving area
	Entrance&Exit: speed warning, traffic density broadcast	Motorway-Entrance&Exit
	Unsignalized intersection: speed warning and vehicle detection	Unsignalized intersection
	Signalized intersection: time advisory, stop warning	Signalized intersection
	Roundabout: route advisory, vehicle detection	Roundabout
	Roundabout with bicycle lane: route advisory, vehicle and bicycle detection	Roundabout with bicycle lane
	5G base station	General
	WIFI	General
	Bluetooth	General

5.3 Summary

This chapter presents the process and results of the first round of interviews with manufacturers and researchers who work on automated driving technology development.

According to the analysis, it can be found that although the first Level 4 automated vehicle could be probably introduced to the market in the next five years, a long period is needed before it is finally accepted by people and replace the conventional vehicle in the future (from 2040-2060). Before the penetration rate of Level 4 automated vehicles arrives 100%, they should be capable of handling the mixed traffic situation as dedicated lanes may not be built due to its high cost and unknown influence on the traffic. Most of the current Level 4 vehicles tests focused on improving the technology of the vehicle to make it fit for the road environment. Nevertheless, the importance of infrastructure in the development and deployment process of automated driving has already been aware by half of the interviewees.

When coming to concrete road situations, signalized intersection and roundabout with bicycle lane are regarded as the most difficult and challenging road situations for Level 4 automated vehicles. For the motorway, interviewees hold the view that Level 4 vehicles could go through nearly all of the segments safely and smoothly, except the entrance and exit.

Physical and digital infrastructure requirements collected in those interviews will be used as input for the next chapter to discuss their feasibilities and map them into different scenarios.

6

Requirements Assessment

This chapter introduces the process to assess requirements collected under specific road situations and map them into most likely scenarios. The research method and data analysis method used in this chapter are the same as in Chapter 5. Besides professional researchers, other critical actors, such as the road authority, service provider and the vehicle authority are involved. In the analysis section, the findings in this chapter are compared with those in Chapter 5. The conclusion of this chapter will address this sub research question '*What are the feasible physical and digital requirements of infrastructure to allow for SAE Level 4 automated driving under most likely scenarios?*'

6.1 Data Collection

6.1.1 Set-up of Interview

The interview contains two sections. The detailed interview protocol can be found in Appendix F.

The first section retains the first two questions of the protocol used in the last research step with some adjustments. Depending on the available interview time and interviewees' responses, extra questions refer to investment issue and business model are asked.

The second section has three objectives: scenario matrix validation, most likely scenario selection, and requirements mapping. To fulfil these aims, the scenario matrix was shortly introduced in the beginning, followed by asking interviewees whether it is plausible or not. If the answer is 'yes,' then they need to select the most likely one. After that, a list of all requirements gathered from manufacturers was given to the interviewees. They could map those requirements to the corresponding scenario based on their expertise.

6.1.2 Interviewees Selection

As stated in the conclusion section of Chapter 3 that, in addition to manufacturers and researchers, service provider and supplier, the ministry, road authorities and vehicle authorities are critical players in this issue as well. Therefore, experts from those organizations are suitable candidates.

To ensure that they have the consistent understanding of the social environment and national conditions, interviewees all come from the Netherlands.

The participants and their expertise field is shown in Table 6.1

Table 6. 1 List of Interviewees (Second round)

Interviewee	Work/Research experience on AD	Expertise	Organization type	Organization
#8	15years	Connected and automated vehicles	Vehicle authority	RDW
#9	20years	Cooperative and intelligent driving	Research institution	Delft University of Technology
#10	6years	Transport policy	Research institution	Delft University of Technology
#11	10years	Smart e-Mobility	Research institution	Hogeschool Rotterdam
#12	11years	Cooperative ITS	Consultancy company	Dynniq
#13	5years	Traffic Managements	Research institution	TNO
#14	20years	Connected and automated vehicles	Road authority	Rijswaterstaat

6.1.3 Conducting the Interview

The procedure to conduct the interview is the same as it in Chapter 5, starting with sending emails to invite experts. Subsequently, face-to-face interviews were carried out. After the interview transcripts have been certificated, they are used to do the data analysis.

6.2 Data Analysis

6.2.1 Descriptive Data Analysis

The first three aspects of descriptive data analysis keep consistency with these in the previous chapter, adding the validation of scenarios, most likely scenario selection and requirements mapping.

- Timeline and attitude towards Level 4 automated driving

Different from 100% positive attitudes towards Level 4 vehicles in the first round interview, some interviewees in the second round interview held the conservative point of view (See Table 6.2). Their average prediction on the year of the first commercial vehicle and final situation also reflect this, which are the year of 2023 and the year of 2058, respectively.

Table 6. 2 Interview results of Timeline and attitude towards Level 4 automated driving (Second round)

Second round interview result of Level 4 automated vehicles' future application

Interviewee	#8	#9	#10	#11	#12	#13	#14	AVE
Attitude towards the future of L4	P*	N*	M*	P	P	P	P	71% P
Market entry time(year)	2025	2018	2025	2025	2022	2020	2030	2023
Become a popular travel modal(year)	2070	2060	2050	2075	2037	2040	2075	2058

* P=Positive Attitude; N=Negative Attitude; M=Moderate Attitude

- Conditions of Level 4 automated driving

In Figure 6.1, one of the experts believed that it is impossible for Level 4 automated vehicles to deal with the mixed traffic and his reason was that only when all vehicles are connected, can they be allowed on public roads. The number of dedicated lane supporters reduced to three when compared with that in the prior round of interviews. Opponent's debate still focused on substantial investment and a shortage of traffic space.

Second round interview result of Level 4 automated vehicles' driving condition

Interviewee	#8	#9	#10	#11	#12	#13	#14
In mixed traffic	Y*	N*	Y	Y	Y	Y	Y
Support dedicated lane	M*	Y	Y	Y	N	N	N

* Y=Yes N=No M=Moderate

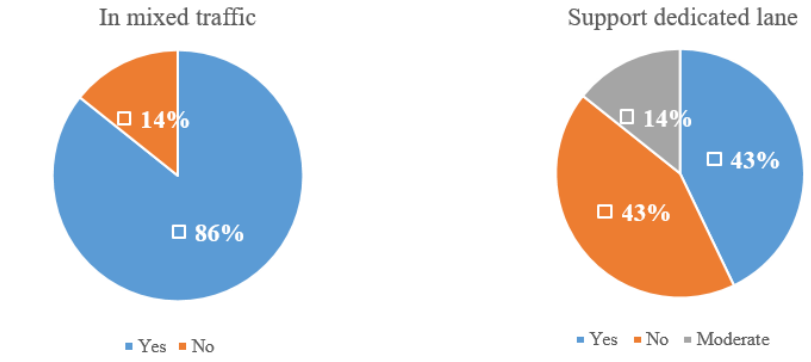

Figure 6. 1 Interview results of conditions of Level 4 automated driving (Second round)

- The necessity of infrastructure upgrades

It can be concluded from Table 6.3 that all interviewees realized the importance of infrastructure upgrades for the development and deployment of automated driving, especially for Level 4 automated vehicles. They also highlighted some cases where infrastructure upgrades are needed and

should be solved in the early days, including the uphill and downhill in tunnels, curve segments and road work zones. Furthermore, they stressed that the current infrastructure needs regular check and good maintenance.

Table 6. 3 Interview results of the necessity of infrastructure upgrades (Second round)

Second round interview result of the necessity of infrastructure upgrades

Interviewee	#8	#9	#10	#11	#12	#13	#14	AVE
Infrastructure upgrades	Ne*	Ne	Ne	Ne	Ne	Ne	Ne	100%NE

* Ne=Necessary

- Validation of scenarios

The scenario matrix received all experts' validation and verification (See Table 6.4).

Table 6. 4 Interview results of the scenario validation

Interview result of scenario validation

Interviewee	#8	#9	#10	#11	#12	#13	#14	AVE
Scenario Validation	Y	Y	Y	Y	Y	Y	Y	100%Y

* Y=Yes

- The response to scenarios

As illustrated in Figure 6.2, Scenario 1 and Scenario 3 regarded as the two most likely scenarios in the future. Their common ground is close cooperation. As a cross-research field, infrastructure upgrades for automated driving require knowledge and information from different stakeholders. Without support from stakeholders, sufficient solutions cannot be discovered, developed and implemented. Also, the ministry cannot decide without consulting involved parties.

During the interviews, the word 'regional difference' was often mentioned. According to one expert's opinion, it is possible that Scenario 1 might happen in the EU countries and Scenario 3 describes the future of Japan and China. The difference between Scenario 1 and Scenario 3 is the amount of public expenditure, which is largely influenced by the local government's policy and preference in advanced transport technology.

The interviewee from Dutch road authority claimed that Scenario 1 fits for present Dutch context that collaboration is practicable but no specific public expenditure for this kind of infrastructure upgrades. So what can be done is limited. In the future, they would try their best to move into Scenario 3 to meet the requirement from the ministry that road infrastructure should be ready for automated vehicles.

Interviewees' response on most likely scenarios

Interviewee	#8	#9	#10	#11	#12	#13	#14
Most likely Scenario	3	1&3	3	2	1 & 3	1	1&3

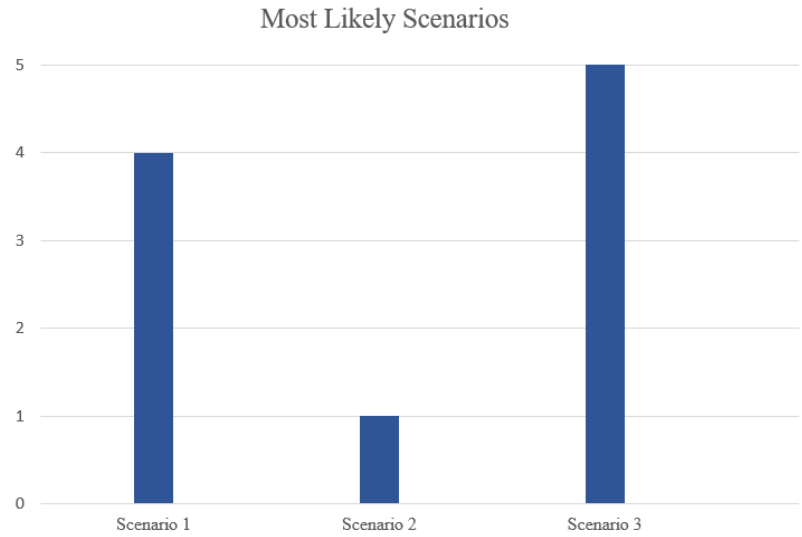

Figure 6. 2 Interview results of the response of scenarios

- Requirements mapping

Each requirement will be mapped into one scenario if at least four experts confirm (See Appendix G). Combined with the conclusion of chapter 5 on most challenging road situations, Table 6.5 and Table 6.6 show the results of requirements mapping after categorizing.

Table 6. 5 Interview results of mapping requirements to Scenario 1

Scenario	Specific road situation	Infrastructure requirements
Scenario 1 Basic Infrastructure	General	Clear and harmonized lane markings, road signs
		Optimal location of (remove) road signs
		HD-maps & Road database
		National/Global road signs and lane markings gallery
		Wireless technology: 5G base station, WIFI, Bluetooth
	Motorway exit/entrance	Speed limit signs
		V2I: speed warning, vehicle detection, traffic density broadcast, weather condition and road condition broadcast
	Unsignalized Intersection	Speed limit signs
		V2I: speed warning and vehicle detection
	Roundabout with bicycle lane	Warning signs for vulnerable road users
		V2I: route advisory, vehicle and bicycle detection

Table 6. 6 Interview results of mapping requirements to Scenario 3

Scenario	Specific road situation	Infrastructure requirements
Scenario 3 Advanced Infrastructure	General	Clear and harmonized lane markings, road signs
		Remove road signs to the road surface
		Sensor Readable lane markings, road signs
		Optimal location of (remove) road signs
		HD-maps & Road database
		National/regional clouds, center
		National/Global road signs and lane markings gallery
		Wireless technology: 5G base station, WIFI, Bluetooth
		Tailored signs or markings for automated vehicle
		Suitable pavement material to deal with new wear pattern
	Motorway exit/entrance	Dedicated lane with barriers/magnetic transmitter
		Brilliant/different color of the merging conflict
		Speed limit signs
		V2I: speed warning, vehicle detection, traffic density broadcast, weather condition and road condition broadcast
	Signalized/Unsignalized Intersection	Speed limit signs
		Countdown for traffic lights
		Radar reflectors in the corner
		Camera sensors for specific situations
		Intelligent traffic lights with flexible timing
		Communicated traffic lights
		V2I: Unsignalized : speed warning and vehicle detection Signalized: time advisory, stop warning
	Roundabout with bicycle lane	Guide marking or road signs for automated vehicle in the roundabout
		Warning signs for vulnerable road users
		Alert device to inform vulnerable road users
		V2I: route advisory, vehicle and bicycle detection

6.2.2 Qualitative Data Analysis

The similar analysis method is carried here as it in the former chapter. In Appendix H, figures demonstrate the coding process can be found. Two summarized categories of qualitative data will be elaborated in the following part.

- Influence factors for infrastructure upgrades

As stated in 6.2.1, interviewees in this round also pointed out the regional difference as one of the main influence factors when making decisions to upgrade infrastructure for automated vehicles. Whether different stakeholders are willing to work closely is another critical factor. The results of the Cost-Benefit Analysis of infrastructure upgrading solutions and policy support also influence

the decision-making process. Equity is a new influence factor that has not been mentioned in the first round interview. Interviewees recognized that when we decide to do something on the infrastructure which may be beneficial for automated vehicles, we should always remember that there must be some people who do not possess or use automated vehicles. So how to protect these people's interest need to be considered because the infrastructure is a public field. Other influence factors are listed in Table 6.7.

Table 6. 7 Interview results of influence factors for infrastructure upgrades (Second round)

Influence factors for infrastructure upgrades			
High Frequency (>4)	**Moderate frequency (>2)**	**Low Frequency (1)**	
Regional difference	Cooperation	Rules and regulation	Operational design domain
Collaboration	Failure mode and frequency	Economy trend	Dimension of road network
Safety	Policy support	The road of road authority	People's preference
Benefits	Public investment	Willingness to pay	Initial Public Offering
Policy support	Private investment		
Equity			

- Stakeholders' concern on infrastructure for automated driving

By comparing concerns of manufacturers and other stakeholders, it can be reported that manufacturers pay more attention to issues that may influence their vital interests. They hope to have more opportunities to test their vehicles so that they can improve the reliability and robustness of their technology. Other players care more about the social effects and focus on building a new regulation system and tax system. Stakeholders' other concerns in Table 6.8 also prove this statement.

Table 6. 8 Interview results of other stakeholders' concerns on infrastructure for automated driving

Stakeholders' concerns on infrastructure for automated driving			
High Frequency (>4)	**Moderate frequency (>2)**	**Low Frequency (1)**	
New regulation system	'Chicken and egg' question	Time saving	Concrete situation
Dedicated lanes	Centralized management	Added value	Neighboring countries
Tax system	Speed limit	Agent-based system	Test permits
Risk	Constructive dialogue	Technical challenge	Negative impacts mitigation
Restricted road segments	Functionality of infrastructure upgrades	Legislation challenge	Specific roads
	Worldwide point of view	Market deployment	Specific users
		Private public partnership	Infrastructure upgrading beforehand

6.3 Summary

Many findings can be concluded in this chapter. In the matter of future application about Level 4 automated vehicles, other critical actors' attitudes are not as positive as that of manufacturers. Regarding different attitudes, the timeline of upgrading infrastructure for automated driving might be different. Besides different prediction on market entry time and popularization period, their concerns differ as well. Thus, balancing the interest of all parties and encouraging them to cooperate is as important as developing plans to implement infrastructure requirements.

According to the analysis result, all of the interviewees agree on the necessity of infrastructure upgrades and most of them support Scenario 1 and Scenario 3. Therefore, these two scenarios will be applied to draw up implementation plans in the next chapter. Requirements that are mapped into scenarios are split into two categories: the general category and the specific road situation category. Those requirements and categories will be applied to make implementation plans in the following research step.

7

Plan Development

In this chapter, implementation plans to upgrade the infrastructure for automated driving based on findings from Chapter 6 will be given. Scenario 1-Basic scenario and Scenario 3-Advanced scenario are the two most likely scenarios regarding the future of automated driving and infrastructure in mixed traffic on motorways and provincial roads. Exit/Entrance of a motorway, together with intersection and roundabout of provincial roads are the most typical road situations. Infrastructure requirements under those road situations and scenarios have been further explained and illustrated in figures and images in the following sub-sections. The EU's report, European Roadmap Smart Systems for Automated Driving (Figure 7.1), is taken as the reference to determine each detailed time period. At the end of this chapter, a stakeholder engagement plan is introduced to get more stakeholders involved and then promote the implementation plan forward.

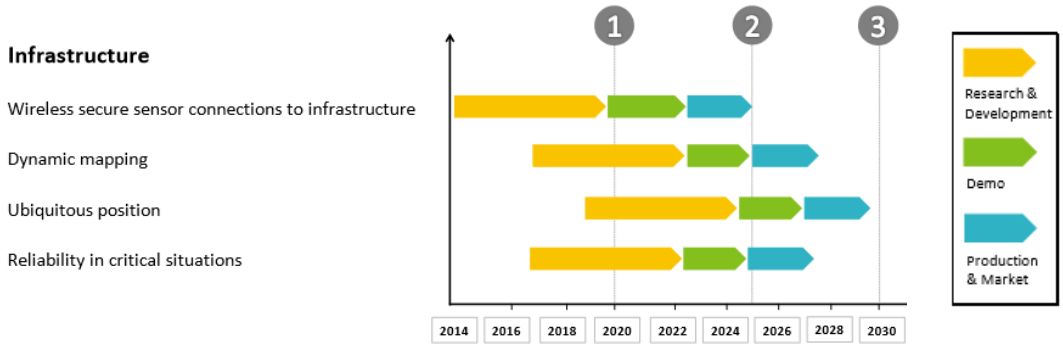

Figure 7. 1 European Roadmap on Infrastructure for Automated Driving (Source: EU, 2015)

7.1 Implementation Plan for Scenario 1

7.1.1 General Plan

Figure 7.2 illustrates how to implement feasible infrastructure requirements collected from interviews with manufacturers under Scenario 1-Basic Scenario, where stakeholders work closely while the public investment for upgrading the infrastructure is limited. The whole process for implementing feasible infrastructure requirements will take over forty years, starting from the year 2018 and until the year 2060 (See the summary of Chapter 6). At that time, driving Level 4 vehicles will become a favourite travel modal for normal citizens. The transition from physical infrastructure to digital infrastructure will happen in the middle of the popularization period, during 2030 to 2035.

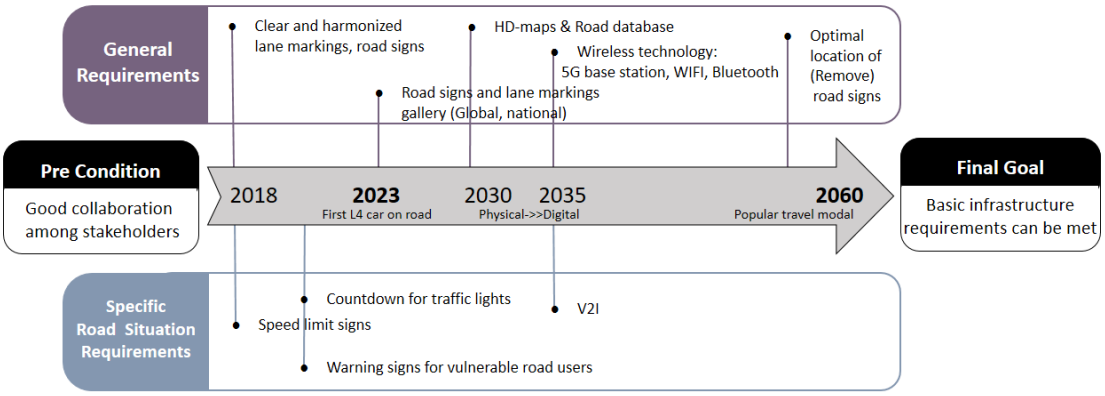

Figure 7. 2 Implementation Plan of Scenario 1 (own illustration)

- Before the Year of 2023

Before the year 2023, at which the first Level 4 vehicle will be introduced to the market, the current infrastructure should be well-maintained and checked carefully to make sure that lane markings and road signs should be at least clear and harmonized. More speed limit signs need to be installed before intersections and on/off ramps. One situation is that in some intersections and on/off ramps, there are no obvious speed limits signs. Another situation is that the distance between the speed limit sign and the intersection/on ramp/off ramp is too short that the response time for the automated vehicles to slow down is not enough after detecting the sign. For human drivers, they are familiar with speed limit rules since they had to obtain their driving licenses, so they can react to these two situations easier and earlier than automated vehicles based on their experiences. However, if the digital maps installed on automated vehicles do not have such information, automated vehicles cannot make preparations as human drivers. Besides, two additional solutions can be considered to improve the traffic efficiency and safety: countdown for traffic lights could remind both automated vehicles and manually-driven vehicles to start in advance, and warning signs for vulnerable road users could call their attention.

- The Year of 2023 to 2030

When Level 4 vehicles are allowed to operate on public roads, their systems must have global or national road signs and lane markings gallery. As road signs and lane markings differ in different countries and applying galleries will require computing time and storage space for vehicles' systems, automated vehicles can choose the requisite gallery before their departure but not install all galleries. If the automated vehicle will cross the border during the trip, its system can change the applied gallery according to the information on the digital map.

- The Year of 2030 to 2035

When the time comes to the year of 2030, the requirement of HD-maps and road database means the transition from physical infrastructure to digital infrastructure. With the development of wireless technology, such as 5G, WIFI, and Bluetooth, Vehicle to Infrastructure communication (V2I) will play an important role in upgrading infrastructure for automated driving. This technology will connect automated vehicles and the infrastructure, providing messages about suggested speeds, suggested routes, road conditions and so on. Additionally, because of the mixed traffic situation, V2I could detect unconnected vehicles coming from the other direction and send this information to automated vehicles, which help the automated vehicle to learn the environment around it in case of emergency.

- The Year of 2060

In the year of 2060, since driving Level 4 vehicles have become a popular travel modal for normal citizens, the location of road signs can be changed to be more suitable for automated vehicles but not for manual cars. There is a possible situation that the penetration of automated vehicles reaches 100%, then the location of road signs can be changed to meet automated vehicles' requirements. Or if the physical infrastructure is replaced entirely by the digital infrastructure, road signs may not be useful anymore. They can even be moved away.

7.1.2 Plan Visualization

To display the feasible infrastructure requirements more visually, Figure 7.3 presents the general infrastructure requirements, the requirements for the exit/entrance of a motorway, the requirements for intersections, and the requirements for the roundabout with bicycle lane respectively.

- General requirements

Among those general requirements, good maintenance of lane markings and road signs and redesign the location (removal) of road signs are two requirements that could improve the environment perception reliability of automated vehicles. Road signs gallery, V2I and wireless technology will benefit the process of decision-making for automated cars. The use of HD maps and road database will give vehicles accurate positioning and route plans before departure.

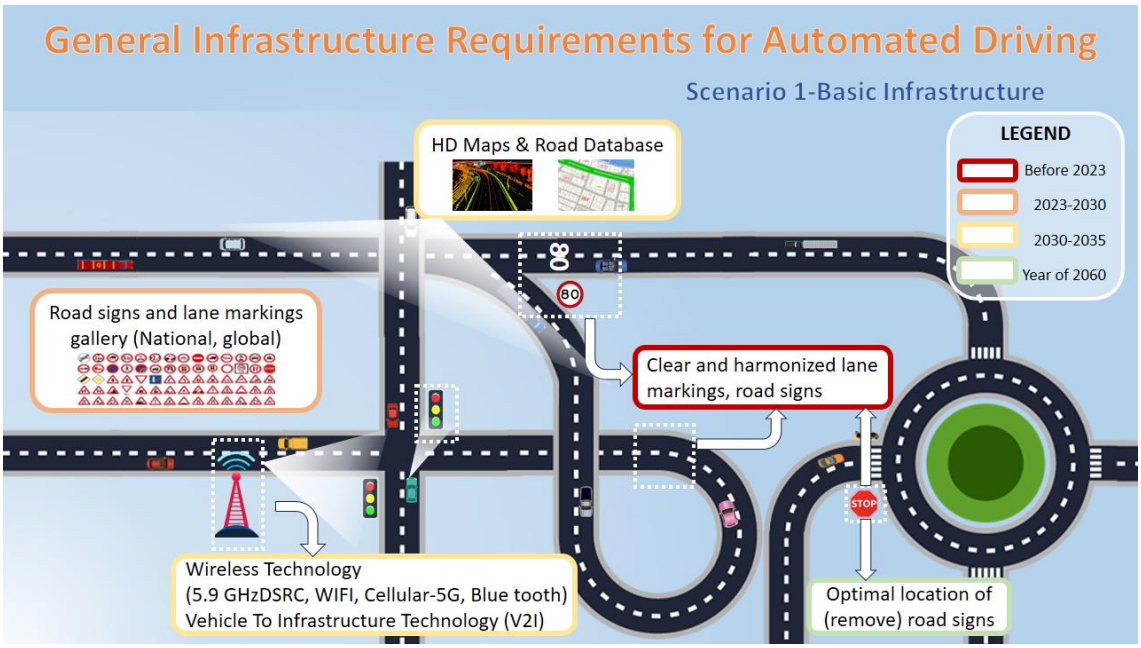

Figure 7. 3 General Infrastructure Requirements in Scenario 1 (own illustration)

- Motorway exit/entrance requirements

There are two main requirements of the infrastructure at exit/entrance of motorways (See Figure 7.4): one is speed limit signs which provide speed information to automated vehicles and are required to be installed before the year of 2023; another is V2I technology which will be applied during the year of 2030 to 2035. A V2I facility is installed in the roadside offering short-range communication with automated vehicles. ① is the communication for a car that will continue to be driving on this motorway. It will receive broadcast about the following weather condition and road condition, such as whether there will be a work zone downstream of the route. For a car about to enter the motorway, V2I will give warning signals about the speed limit and vehicles driving on the motorway (②). If a car is driving on an off-ramp, besides the speed warning signal, V2I will also tell the car the traffic density of the forward road (③).

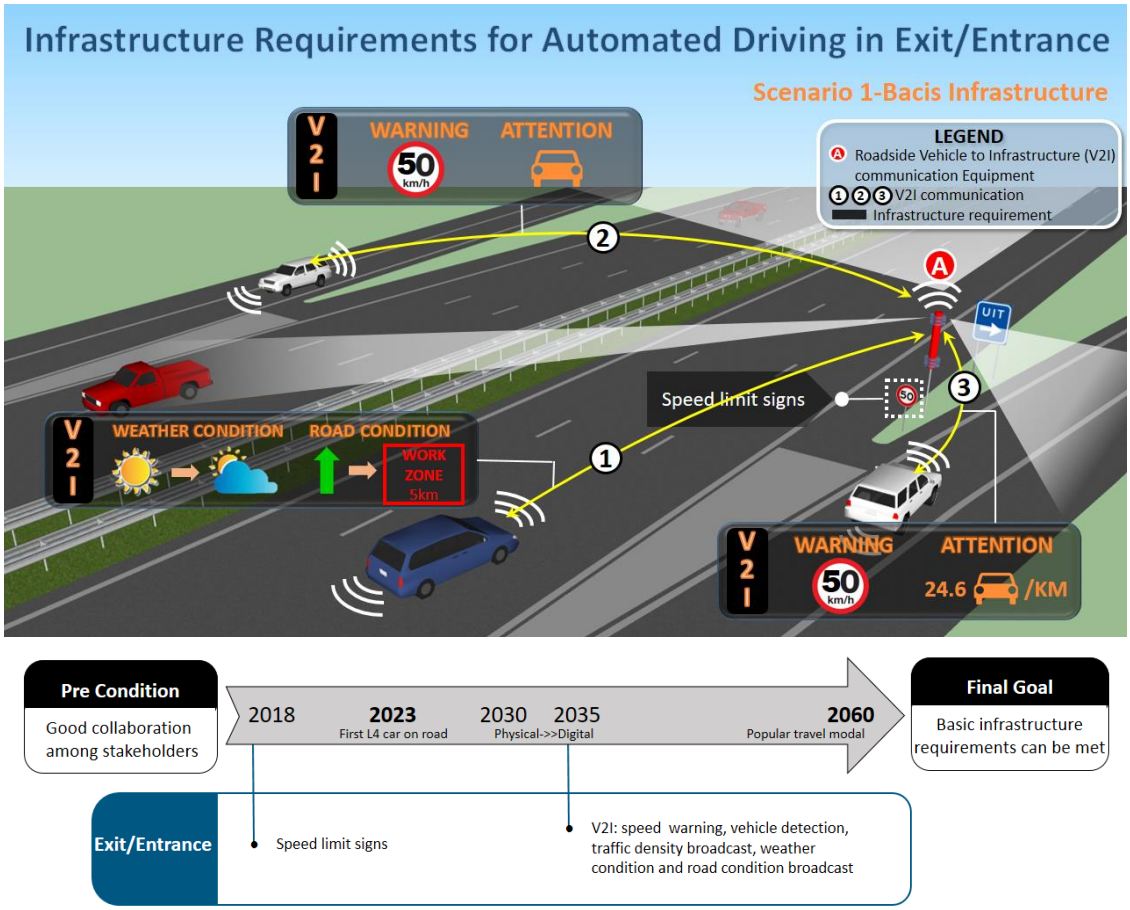

Figure 7. 4 Infrastructure Requirements of Motorway Exit/Entrance in Scenario 1 (own illustration)

- Intersection requirements

Figure 7.5 demonstrates the situation of intersection (signalized and unsignalized). For signalized intersections, countdowns are required to be installed before the year of 2023 which can provide timely information to both human drivers and automated vehicles when they make decisions on stop or start. If there is no traffic signal, speed limit signs are requisite and V2I technology shall be able to detect the position and velocity of all vehicles at the intersection and offer this kind of information to automated vehicles. Meanwhile, the automated vehicle should always slow down before reaching the intersection (①).

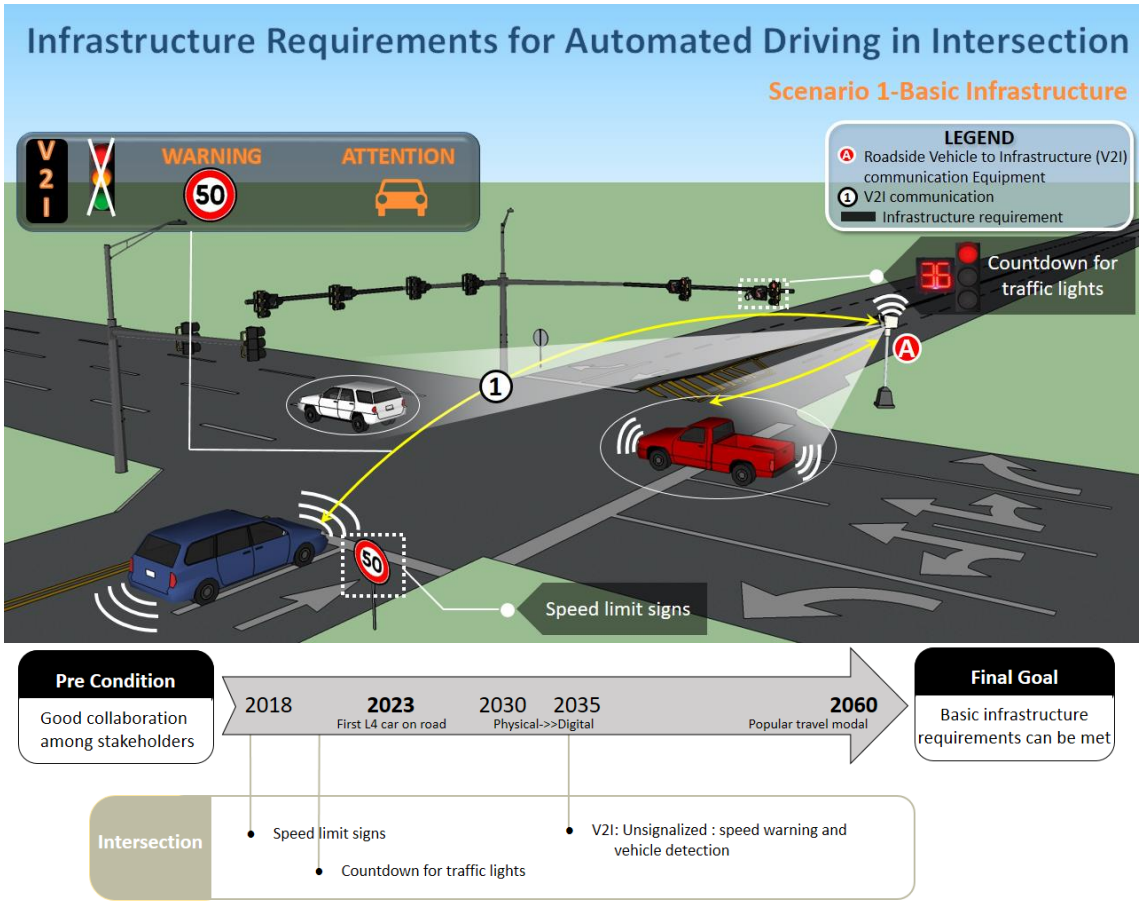

Figure 7. 5 Infrastructure Requirements of Intersection in Scenario 1 (own illustration)

- Roundabout with bicycle lane requirements

In the roundabout with bicycle lane situation (Figure 7.6), adding warning signs to tell pedestrians that automated vehicles are allowed here is essential and need to be finished before the first introduction of Level 4 vehicles. V2I communication could guide the automated car how to enter and bear off the roundabout and help the vehicle to sense other vehicles and vulnerable road users.

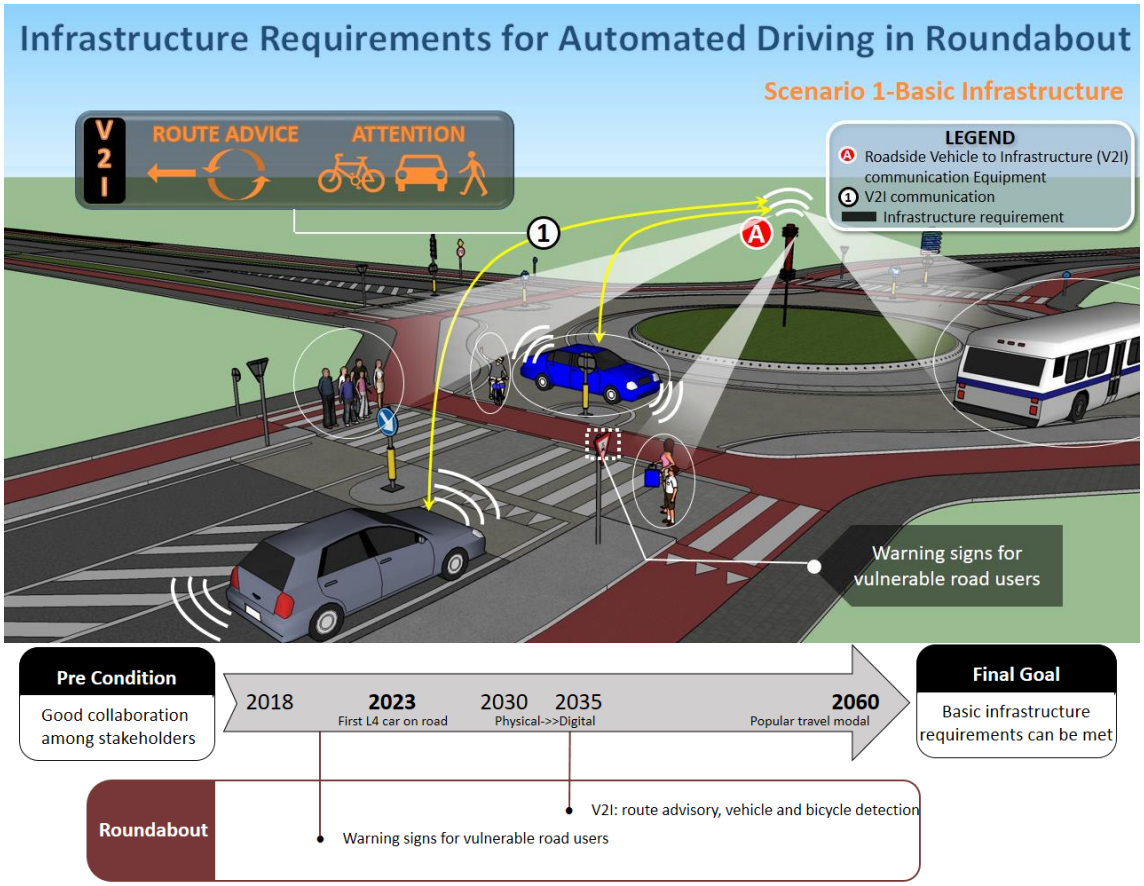

Figure 7. 6 Infrastructure Requirements of Roundabout in Scenario 1 (own illustration)

7.2 Implementation Plan for Scenario 3

7.2.1 General Plan

The following Figure 7.7 is the timeline to implement feasible infrastructure requirements collected from interviews with manufacturers under scenario 3-Advanced Scenario. Under this scenario, not only the cooperation level among stakeholders is high, but also the government is willing to upgrade the infrastructure for automated driving. Therefore, the public expenditure is high. Compared with scenario 1-Basic scenario, the process is ten years shorter, ending in the year of 2050. The transition from physical infrastructure to digital infrastructure will happen in the middle of the popularization period, during the year of 2025 to 2030.

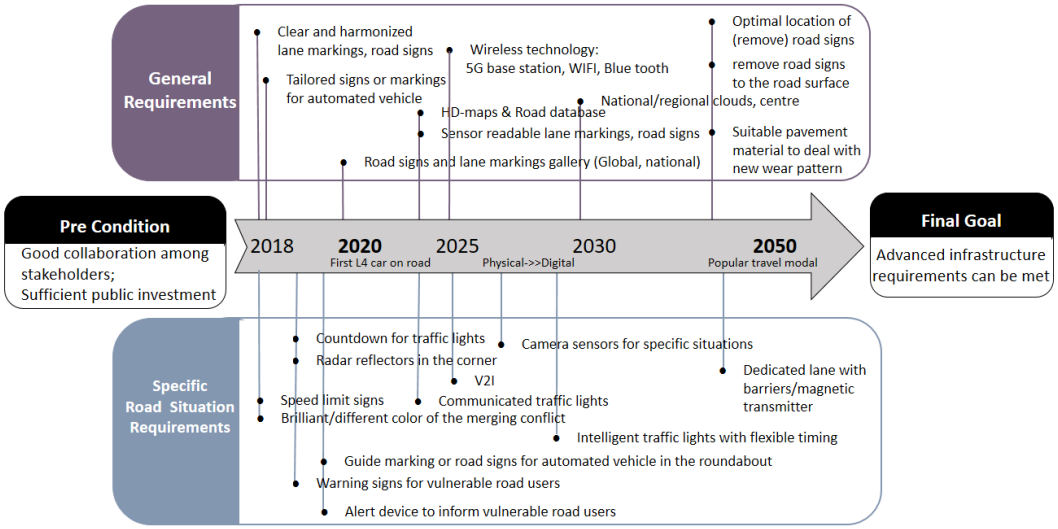

Figure 7. 7 Implementation Plan of Scenario 3 (own illustration)

- Before the Year of 2020

The time of the first commercial Level 4 automated vehicles will be brought forward to the year of 2020. Before that, in addition to clear road signs and more speed signs, tailored signs or markings for automated vehicles shall be designed and the merging conflict shall be painted with brilliant colours. To protect other road users, warning signs and alert device are required. Those physical infrastructures which do not involve new technology, such as countdown for traffic lights and radar reflectors, can also be installed.

- The Year of 2020 to 2025

When Level 4 vehicles are released, global or national road signs and lane markings gallery is mandatory for them. Then, with the development of technology, road signs and lane markings are readable for vehicle sensors. Furthermore, HD-maps and road database will be ready for automated driving and traffic lights shall become communicated.

- The Year of 2025 to 2030

When V2I and wireless technology become capable, the focus of infrastructure for automated driving will turn from physical to digital. National or regional clouds and traffic management centre will be needed to store data. For some specific road situations, camera sensor will help the vehicle to detect the surrounding environment. Moreover, the flexible timing system will be used in some intelligent traffic lights to improve traffic efficiency.

- The Year of 2050

Dedicated lanes will only be considered when the penetration rate of Level 4 vehicles arrives at a relatively high Level. In the end, physical road signs can be removed to the road surface or are not useful for automated vehicles, and new pavement material for automated vehicles will be applied.

7.2.2 Plan Visualization

Figure 7.8-Figure 7.11 shows the general infrastructure requirements, requirements in exit/entrance of motorway, requirements in intersection and requirements in a roundabout with bicycle lane respectively.

- General requirements

Figure 7.8 demonstrates general infrastructure requirements during different future time period.

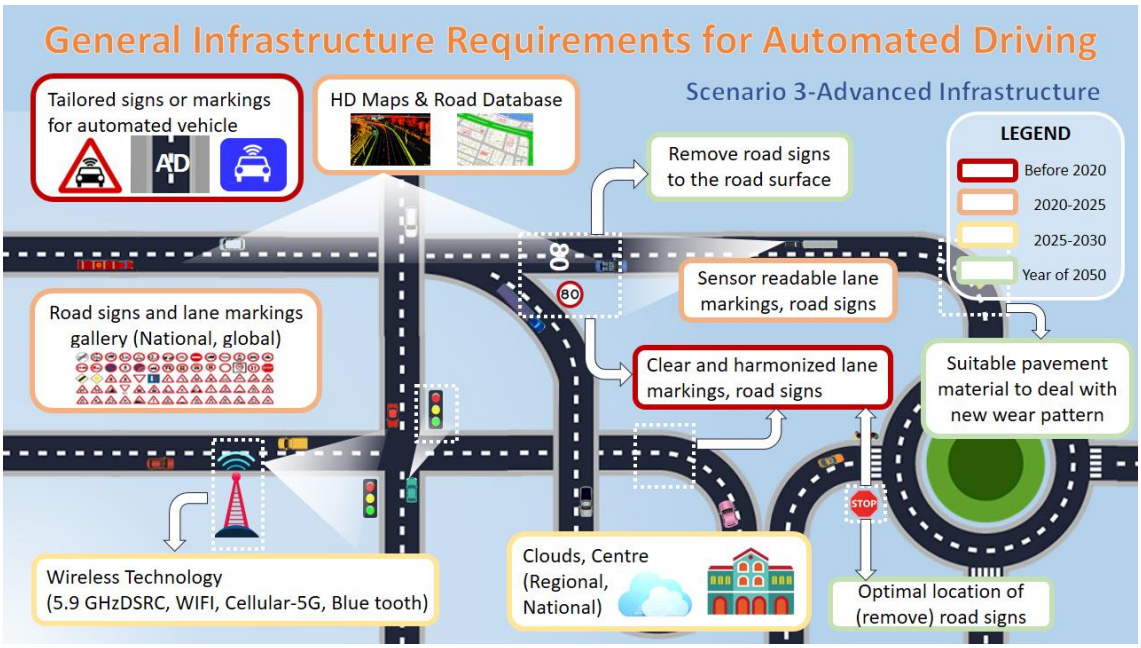

Figure 7. 8 General Infrastructure Requirements in Scenario 3 (own illustration)

- Motorway exit/entrance requirements

In Figure 7.9, four infrastructure requirements for motorway exit/entrance are demonstrated, including speed limit signs, brilliant/different colour of the merging conflict, V2I technology and dedicated lane. Speed limit signs and brilliant/different colour of the merging conflict are requirements before the year of 2020. Two solutions can be applied to separate dedicated lanes for automated vehicles and normal lanes for conventional vehicles in the year of 2050: building barriers or inserting magnetic transmitter into the road surface. Functions of the V2I communication are the same as those in Scenario 1 (Entrance: speed warning and vehicle detection; Exit: speed warning and traffic density broadcast; straight segment: weather condition and road condition broadcast).

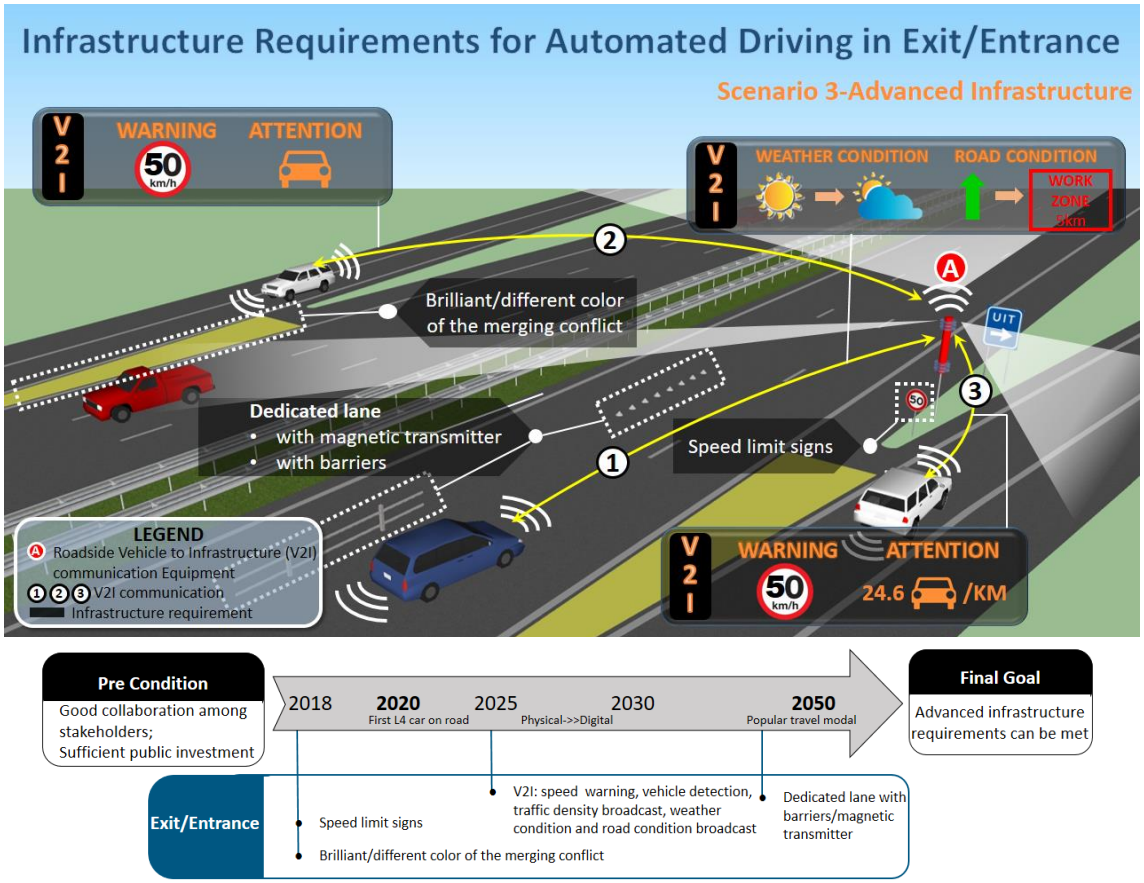

Figure 7. 9 Infrastructure Requirements of Motorway Exit/Entrance in Scenario 3 (own illustration)

- Intersection requirements

The following Figure 7.10 shows the situation of intersection (signalized and unsignalized). In Scenario 3 (Advanced infrastructure), radar reflector and camera sensor are two additional requirements compared with Scenario 1(Basic infrastructure) before the first commercial Level 4 automated vehicle is allowed to drive on public roads. Signalized intersection is simpler for automated vehicles to cross than an unsignalized intersection. For signalized intersection, the traffic lights are not only communicated (before the year of 2025) but also intelligent as their timing system is flexible, which may reduce the vehicle's waiting time at the intersection. Therefore, V2I technology for signalized intersection shall have the function that providing time advisory and giving stop signal to the automated vehicle before it arrives at the intersection. If the intersection is unsignalized, V2I shall send a message to the vehicle containing speed limit information and peripheral vehicle information.

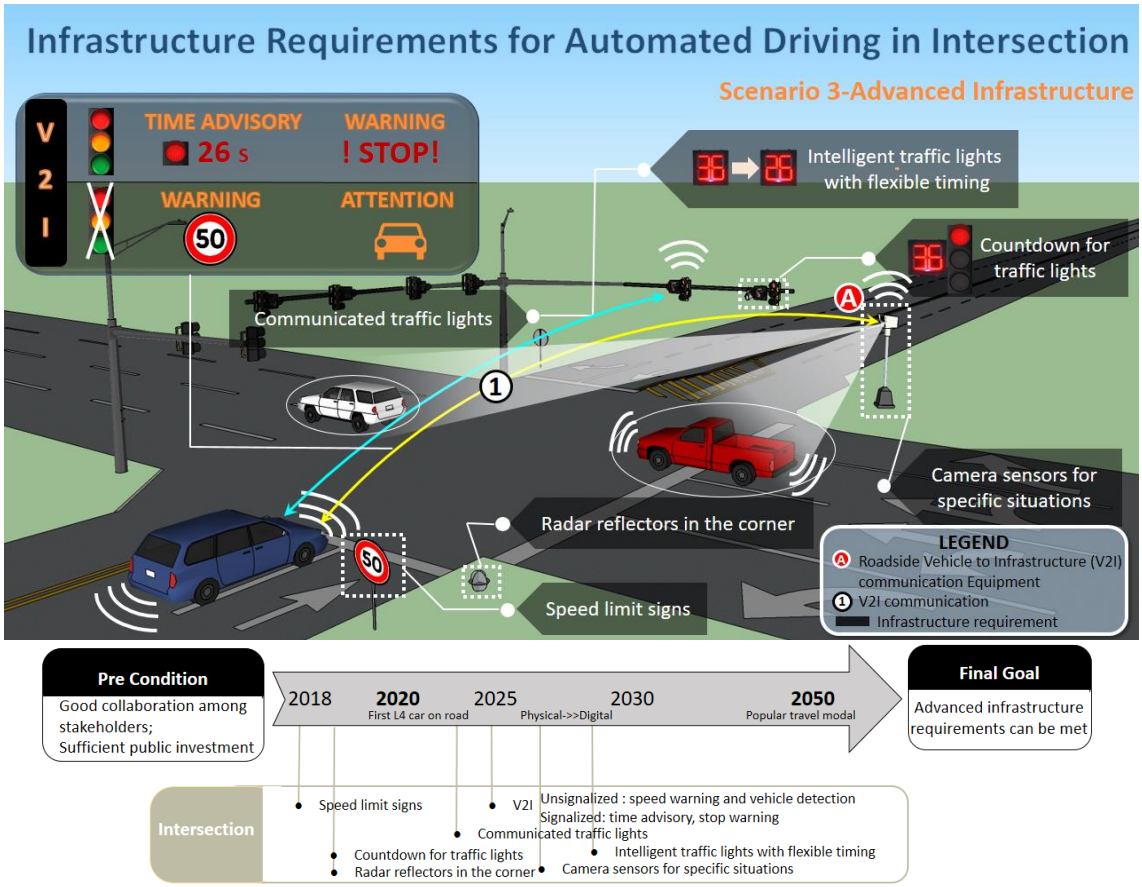

Figure 7. 10 Infrastructure Requirements of Intersection in Scenario 3 (own illustration)

- Roundabout with bicycle lane requirements

Because available investment in Scenario 3 (Advanced infrastructure) is more than that in Scenario 1 (Basic infrastructure), an alert device that can make a sound when automated vehicles are passing will be used to protect vulnerable road users, apart from warning signs (See Figure 7.11). The purpose of guide markings or road signs is to help automated vehicles to plan their routes when arriving at the roundabout as vehicles may be confused about the traffic rules of the roundabout. These two requirements shall be met before the year of 2020. V2I communication could also meet such a requirement to give route advisory and the information of unconnected vehicles.

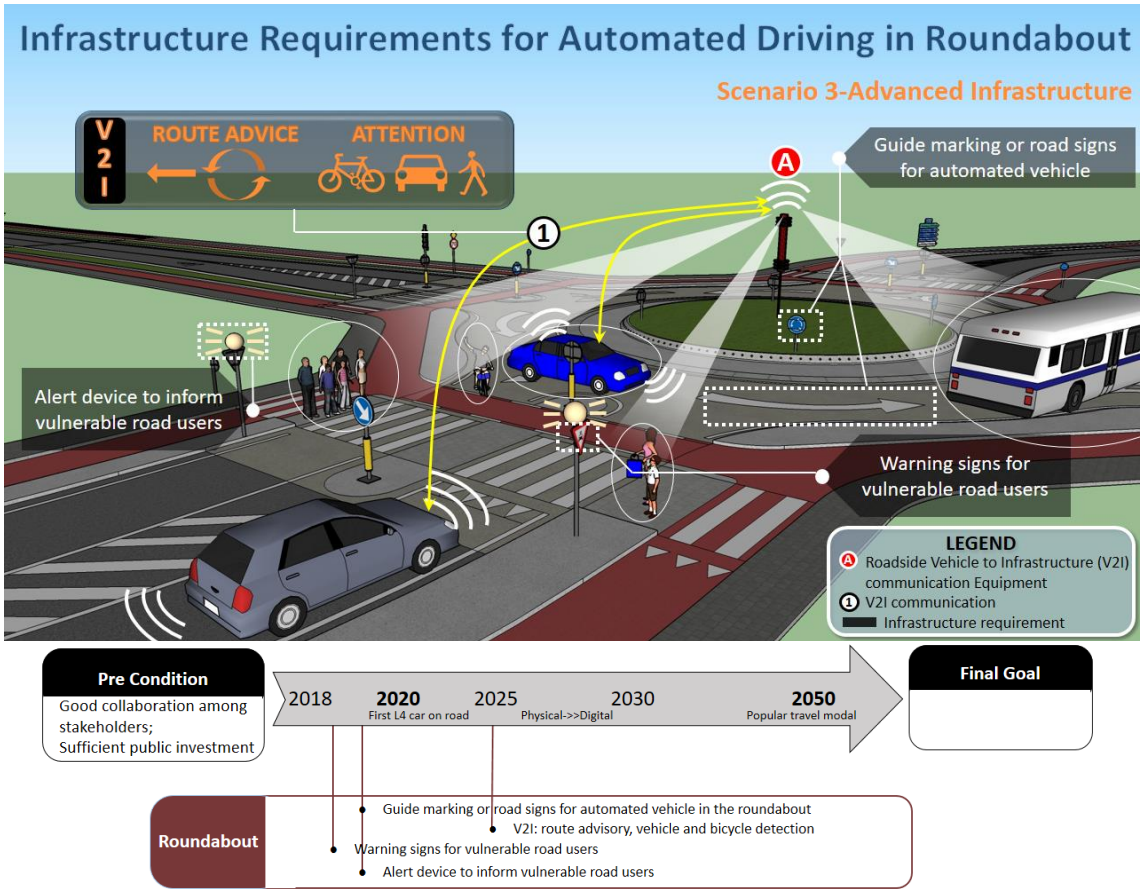

Figure 7. 11 Infrastructure Requirements of Roundabout in Scenario 3 (own illustration)

7.3 Stakeholder Engagement Plan

Both Scenario 1 (Basic infrastructure) and Scenario 3 (Advanced infrastructure) require close collaboration among stakeholders. It is important that there is support from the stakeholders. On the one hand, engaging stakeholders could prevent resistance emerging which may delay and endanger the project execution. On the other hand, only with information and knowledge from other stakeholders can road authorities implement the plans smoothly and speed up the process.

The engagement plan uses the five Levels of stakeholder involvement (Inform, Consult, Involve, Collaborate, and Empower) as described by Byson (2004), supplemented with actions if possible.

The engagement plan applies the conclusion of Chapter 3, supplemented with actions if possible.

Table 7.1 shows the preferred engagement options for all stakeholders (The Ministry of Infrastructure and Water Management, Road authorities, Vehicle authorities, Manufacturers, Service provider and supplier, Research institutes, Car drivers, Insurance companies). These options are identified to adhere to the interests of the stakeholders and to be able to exploit the available expertise of some of the stakeholders. By doing so, stakeholders are more likely to understand the gravity of the situation and will therefore sooner support the implementation plan.

Table 7. 1 Stakeholder Engagement Plan

Stakeholder	Engagement Action
The Ministry of Infrastructure and Water Management	Empower- Infrastructure and mobility are the responsibilities of the Ministry of Infrastructure and Water Management, so they will necessarily be involved. Road authorities and vehicle authorities are both execution agencies of it. The ministry aims to take the lead in the development of automated vehicles and prepare the Netherlands for their implementation, which shows the positive attitudes. Furthermore, the Ministry also decides on how much public expenditures are available for infrastructure upgrading. The road authorities should report to the Ministry regularly about the current progress and outcomes.
Road authorities	Collaborate-Road authorities will take the role as coordinators and executors during the implementation phases. Different Levels of road authorities can work together and organize meetings and workshops to promote communication and collaboration among stakeholders.
Vehicle authorities	Consult-As vehicle authorities are responsible for automated vehicle test applications, and they have long-term collaboration activities with manufacturers, by consulting them, where automated vehicles meet difficulties during road tests can be learned. They could also provide accesses to contact manufacturers and opportunities for establishing a cooperative relationship
Manufacturers	Involve-Infrastructure upgrades will undoubtedly influence the functions of automated cars. By involving manufacturers who have the most knowledge of how vehicles at different automation levels operate, can help to find effective solutions and give preferences among infrastructure updates alternatives. Collaborate-Although road authorities know the road infrastructure well, but till now, most of their work is about physical infrastructure. In some innovative fields, they need to collaborate with manufacturers to seek for the best solutions.
Service providers and suppliers	Involve-Service providers and suppliers need to be involved in the preliminary phase to assess the feasibility of each solution. For example, telecom companies know wireless technology, and pavement material suppliers are familiar with every kind of pavement material. By involving them, the feasibility of each

	solution can be learned and how much will this solution cost also be known.
Research institutes	Consult-Research institutes have a lot of research projects and expertise in different fields. They could help the road authorities to assess impacts of each implementation action and even put forward new solutions.
Car drivers	Inform-Car drivers are day-to-day users of road infrastructure and automated vehicles, so they need to be informed about how the infrastructure will be changed. By informing them, they will be kept abreast of the last implementation action. This could reduce the risk of receiving resistance from them.
Insurance companies	Inform-Insurance companies need external information to decide their policies. Infrastructure changes will influence the safety and risk of driving a car. By informing them, they can adjust their policies with the upgrading phase of infrastructure.

7.4 Summary

In this chapter, two different implementation plans regarding two most likely scenarios in the future are visualized. For Scenarios 1 (Basic infrastructure), the implementation process will run for forty years while it will be shortened to thirty years in Scenario 3 (Advanced infrastructure). V2I technology and HD-maps are two core measures in both Scenario 1 and Scenario 3 as the implementation of them means transformation from physical infrastructure to digital infrastructure. Dedicated lanes may only become a truth in Scenario 3 due to its potentially high cost and influence on the whole traffic efficiency. The time-based and scenario-based implementation plans are also supported by a stakeholder engagement plan, which applying five Levels to design measures to strengthen cooperation and reduce the risk of resistance.

Part IV

Conclusion, Recommendation and Discussion

Chapter 8 Conclusion and Recommendation

Chapter 9 Research Reflection

8

Conclusion and Recommendation

This chapter wraps up the research thesis by discussing the research findings and drawing up the final conclusion. The aim of concluding research findings is to address sub-questions with the overall conclusion giving the answer to the main research question: *What are the road infrastructure requirements to allow for SAE Level 4 automated driving?* At the end of this chapter, recommendations are provided for road authorities to implement the suggested plans of this research.

8.1 Research Findings

Through reviewing the literature and analysing involved stakeholders, the first sub research question: W*hat are the current research and market status of automated vehicles and infrastructure* is addressed.

After that, following the logic of Schwartz's (2004) methodology, four plausible scenarios describing the possible future are constructed based on two driving forces, the public expenditure and the cooperation among stakeholders. According to interviewees' opinions that Scenario 1-Basic Infrastructure Scenario (low public expenditure and close cooperation) and Scenario 3-Advanced Infrastructure Scenario (high public expenditure and close cooperation) are regarded as the most likely scenarios. The second sub research question: *What are the future scenarios regarding infrastructure for automated driving?* is answered.

The results of interviews show that most interviewees hold positive attitudes towards Level 4 automated vehicles and agree on the necessity of infrastructure upgrading. Considering a set of influencing factors, such as people's acceptance, the development of technology and so on, two timelines (2020-2050, 2023-2060) can describe the popularization process, which should also be applied to design the infrastructure upgrade procedure. Figure 8.1 is the suggested implementation plan, which gives the answer to the third and fourth sub-question: *What are the feasible physical and digital requirements of infrastructure to allow for SAE Level 4 vehicle automation under most likely scenarios?* and *How to upgrade the road infrastructure under the most likely scenarios?*

Table 8. 1 Infrastructure requirements implementation plan

Scenario 1 Basic infrastructure (Good collaboration among stakeholders)		Scenario 3 Advanced infrastructure (Good collaboration among stakeholders; Sufficient public investment)	
Time period	Infrastructure solutions	Time period	Infrastructure solutions
Before 2023	• Clear and harmonized lane markings, road signs • Speed limit signs • Countdown for traffic lights • Warning signs for vulnerable road users	Before 2020	• Clear and harmonized lane markings, road signs • Tailored signs or markings for automated vehicle • Speed limit signs • Brilliant/different colour of the merging conflict • Countdown for traffic lights • Radar reflectors in the corner • Warning signs for vulnerable road users • Alert device to inform vulnerable road users • Alert device to inform vulnerable road users
2023- 2030	• Road signs and lane markings gallery (Global, national)	2020- 2025	• Road signs and lane markings gallery (Global, national) • HD-maps & Road database • Sensor readable lane markings, road signs
2030- 2035	• HD-maps & Road database • Wireless technology (5G base station, WIFI, Bluetooth) • V2I technology	2025- 2030	• Wireless technology (5G base station, WIFI, Bluetooth) • V2I technology • Camera sensors for specific situations • Intelligent traffic lights with flexible timing • National/regional clouds, centre
2060	• Optimal location of (Remove) road signs	2050	• Optimal location of (Remove) road signs • remove road signs to the road surface • Suitable pavement material to deal with new wear pattern

			• Dedicated lane with barriers/magnetic transmitter
Final Goal	Basic infrastructure requirements can be met	Final Goal	Advanced infrastructure requirements can be met

With all sub-research questions addressed, the main research question can now be answered. The next section gives the answer to the main research question: *What are the road infrastructure requirements to allow for SAE Level 4 automated driving?*

8.2 Overall Conclusion

To allow for SAE Level 4 automated driving, the road infrastructure requirements are different under two scenarios where the amount of public expenditure and the popularization period of Level 4 automated vehicles differ as well.

Scenario 1(Basic infrastructure) starts from the year of 2023 and ends at the year of 2060, containing basic infrastructure requirements, emphasize road signs and lane markings, HD-maps and road database, V2I technology and so on. Relatively speaking, Scenario 3 (Advanced infrastructure) contains more high-cost requirements, such as intelligent traffic lights, radar reflectors and camera detectors, dedicated lanes and new pavement material. And the whole time period is shortened to thirty years.

Most findings show quite some consistency with the literature, such as the prediction of Level 4 future application and some infrastructure requirements. Whereas the research finds that the implication of physical infrastructure on automated driving is as important as digital infrastructure and requirements on physical infrastructure are even more than that on digital infrastructure. But it is certain that there is a trend of transition from physical infrastructure to digital infrastructure, which will happen after the first Level 4 automated vehicle is introduced to the market.

Although infrastructure requirements have already been collected and implementation plans have been made, there is still a long way to for the practical application. Aspects related to stakeholders' attitudes and expenditure (both public and private) on infrastructure upgrading projects are defined as major influencing factors in this issue. It is believed that by engaging more stakeholders and seeking for more cooperating opportunities, road authorities can implement infrastructure upgrades more smoothly and achieve their goal of preparing the road network ready for coming automated vehicles.

8.3 Recommendations for Road Authorities

A set of recommendations for road authorities who will take the role as coordinators and executors to implement infrastructure upgrading plans are:

- Conduct the Cost-Benefit Analysis (CBA) for each infrastructure requirement solution

A CBA not only provides the Ministry with a clear overview on future expenditure and benefits of infrastructure upgrades for automated driving, if the result is positive, it can also be used to raise people's awareness on the necessity of upgrading infrastructure for automated vehicles.

- Set concrete collaboration forms and rules with manufacturers

Instead of seeking for close cooperation with manufacturers, building joint development on some concrete aspects rather than on all aspects may be more acceptable for manufacturers. The choice on the collaboration form should be flexible while collaboration rules can be strict to protect manufacturers from losing their core technology.

- Expand the scope of cooperation

In addition to building one-to-one cooperation relationship with manufacturers, road authorities can also initiate joint cooperation projects with vehicle authorities, research institutes and suppliers. For instance, the application of V2I technology needs mature wireless network technology which is provided by telecom companies. Research institutes can work on more innovative solutions to upgrade infrastructure for automated vehicles. Vehicle authorities can help arrange road tests of infrastructure solution to figure out 'no regret' measure. The aim of road authorities should not be

restricted to 'win-win', but taking the role of a coordinator to create 'multi-win' for most stakeholders. Through close cooperation with more parties, the private expenditure may be available for infrastructure upgrading and new kinds of business model can be designed by road authorities to operate those new infrastructures.

- Design open process

During the design phase of infrastructure upgrades, road authorities should design workshops and meetings to learn more stakeholders' opinions before making a decision on adopting which solution, rather than inform stakeholders about their decisions. This can be beneficial for reducing resistance from stakeholders in the implementation phase and learn potential risks based on stakeholders' knowledge.

- Keep the international perspective

Keeping the international perspective is especially important for European countries where vehicles may cross the borders without even noticing it. If the infrastructure for automated vehicles in one country is not the same in another country, automated vehicles' functionalities may be influenced. Furthermore, other countries' experience can also be a good reference for practical application.

9

Research Discussion

Aside from the content-related outcomes of the scenario planning and two rounds of expert interviews, some effort was given to reflecting upon the limitations of the research scope and methods. This chapter is organized into three sections: the first two discuss the limitations of the research scope and methods; the third one gives recommendations for possible further research based on those limitations.

9.1 Limitations of the research scope

- The necessity of perpetual continuous infrastructure upgrades

One fierce debate regarding the future application of automated vehicles is that how the penetration rate will evolve. In this research, we make an assumption that automated vehicles will reach the market in recent years and the penetration rate of them will finally evolve to a relatively high level. Therefore, with the increasing penetration rate of automated vehicles, the demand for infrastructure upgrades also rises up. However, another future situation may also appear that due to the expensive price and people's distrust, the penetration rate of automated vehicles will not arrive at the high level as previously predicted. In this case, the necessity of perpetual continuous infrastructure upgrades may be doubted.

- Level 4 automated driving

Through comparing the technology of different Levels automated vehicles and their market status, we select SAE Level 4 automated vehicles as the research object (Level 3 is criticized on its request for driver' time-to-time intervention and Level 5 will not be driving on the road before 2075. (Shladover, 2015; Farah, 2016; SDFE, 2017; GM, 2018; Tesla, 2018; Volvo, 2018)). Although the result of two rounds of expert interviews shows that most interviewees hold positive attitudes towards Level 4 automated vehicles, whether they will become the 'mainstream' automated vehicles remains unknown. Level 3 automated vehicles may also not cope with the current infrastructure as they need to perform the entire DDT. Only when the ADS fails, the DDT fallback will be the driver. This is also a gap between what is declared by manufacturers and the reality regarding Level 3 that a level 3 automated vehicle can play all DDT but a driver is still needed to take back the control of the vehicle when it is necessary.

- Dutch context

Given the feasibility of contacting interviewee candidates, the stakeholder analysis is based on

Dutch context. In the Netherlands, the Ministry of Infrastructure and Water Management is in charge of all infrastructure projects nationwide while different levels of road authorities are in charge of different road infrastructure. Motorways are operated by Rijkswaterstaat, a public agency of the Ministry and provincial roads are under the operation of provincial road authorities. Meantime, the national vehicle authority, RDW, is also a public agency of the Ministry. However, these administrative relations may be different in other countries, which may influence the interdependency between two stakeholders. As mentioned by many interviewees that when we making the decision on how to upgrade the road infrastructure for automated driving, we must always remember the regional difference.

- Lack of cost estimation

From the perspective of project management, a project is constrained by time, scope and cost (Atkinson, R., 1999). In this research, we design implementation plans for upgrading infrastructure which contains the project scope and the timeline, but the cost is not given. One reason is that in the implementation plan, there are a lot of new technologies whose market prices have not be available; another reason is that this research does not contain a case study that can be used to do cost estimation.

9.2 Limitations of the research methods

- Lack of enough quantitative research data

The main research method applied in this research to collect data is the expert interview. Therefore, the data relies on interviewees' subjectivisms. Then, during the analysis phase, answers of interviewees are classified into different categories. In this research, we did the descriptive data analysis on the timeline of Level 4 automated driving, interviewees' attitudes towards Level 4 automated vehicles and infrastructure upgrades, and calculated the frequency of keywords appeared during interviews. But the lack of enough quantitative research data, such as the minimum distance between the intersection and the speed limit signs, the number of V2I facilities and so on, put difficulties to present research results.

- Limit sample size

During the research, we interviewed three manufacturers. Although they come from different manufacturing companies in different countries, three interviewees may not represent the main opinions of all manufacturers. Getting access to manufacturers who are willing to be interviewed is not easy. Some companies even state that they do not accept any interviews. Nevertheless, because different manufacturers develop their automated vehicles with different technologies, exploring more infrastructure requirements is necessary to approach more manufacturers to expand the sample size.

- Accuracy of scenarios

Scenarios provide future possibilities to category our findings in this research. However, because of the time limit for this research, we did not follow the entire process to construct scenarios. Instead of asking experts to rank influencing factors, we finished this step based on the literature and our expertise and then validated those scenarios with interviewees. In addition to this reason, the drawback of the scenario planning approach itself may also influence the accuracy of scenarios. As the building of scenario matrix uses two main drivers whose uncertainties and impacts are the highest, if other key uncertainties are selected, the results could be argued (Bishop, Hines & Collins, 2007).

- Lack of worldwide data resource

To figure out the most challenging road situations for automated vehicles, we studied disengagement report of automated vehicle road test prepared by the Department of Motor Vehicles in California (Favarò et al., 2018). We failed to search for similar reports of other countries during the research time.

9.3 Recommendations for further research

The limited scope of this research leaves room for improvements and other aspects to relate to. Other Levels of automated driving can be further studied and other methods can be applied to the problem and assumptions could be further specified. Combined discussion of section 9.1 and 9.2, possible recommendations to conduct further research are listed as follows:

- Other methods to map future infrastructure requirements

This research uses scenario planning to describe different future situations where infrastructure requirements for automated driving may also be different. In Nitsche et al. (2014)'s study, they linked infrastructure requirements with different automated driving systems. Other methods, for instance, some safety analysis models can also be applied to investigate infrastructure requirements for automated driving.

- Involve more manufacturers

To make the data resource more various, more manufacturers can be selected as interviewees. Requirements from those new interviewees can be compared with the conclusion of this research. Or findings of this research can be used as interview questions to verify whether those requirements are regarded as necessary by most manufacturers.

- Assess the benefits of infrastructure requirements

There is another research focus that linking each infrastructure requirement with the corresponding automated driving technology to study the benefit of each requirement. For instance, clear and harmonized road signs and lane markings improve the accomplishment of environment perception functionality of automated vehicles while V2I technology is more beneficial for the decision-

making functionality. However, given the budget limit, we cannot meet every requirement but to figure out the most efficient ones according to their benefits and costs.

- Estimate the cost of infrastructure upgrades

The suggested method to estimate the cost of infrastructure upgrades is a case study. It is difficult to give an overall cost without detailed information on the current road infrastructure. One of the research findings also states that requirements on infrastructure for automated driving are not the same in different countries, even in different regions. Therefore, only with a road case whose present infrastructure database is complete, can we estimate the possible cost to upgrade this road and make it more capable of automated vehicles.

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Appendices

Appendix A

Steps to build macro scenarios

Figure A.1 gives an overview of the whole process described by Peter Schwartz (1991): ‘

1. Identify Focal Issue or Decision - begin with a specific, important decision that has to be made;

2. Key Factors in the Local Environment - list key factors influencing the success or failure of that decision;

3. Driving Forces - list driving forces in the macro-environment that influence the key factors (this usually requires research);

4. Rank by Importance and Uncertainty - identify two or three factors that are most important and most uncertain

5. Selecting Scenario Logics - select just a few scenarios whose differences make a difference to decision-makers;

6. Fleshing Out the Scenarios - return to key factors and driving forces and weave the pieces together in the form of a narrative;

7. Implications - return to the focal decision, rehearse the scenarios, and ask questions such as how robust the decision or strategy is across all the scenarios;

8. Selection of Leading Indicators - identify a few indicators to monitor in an ongoing way.’

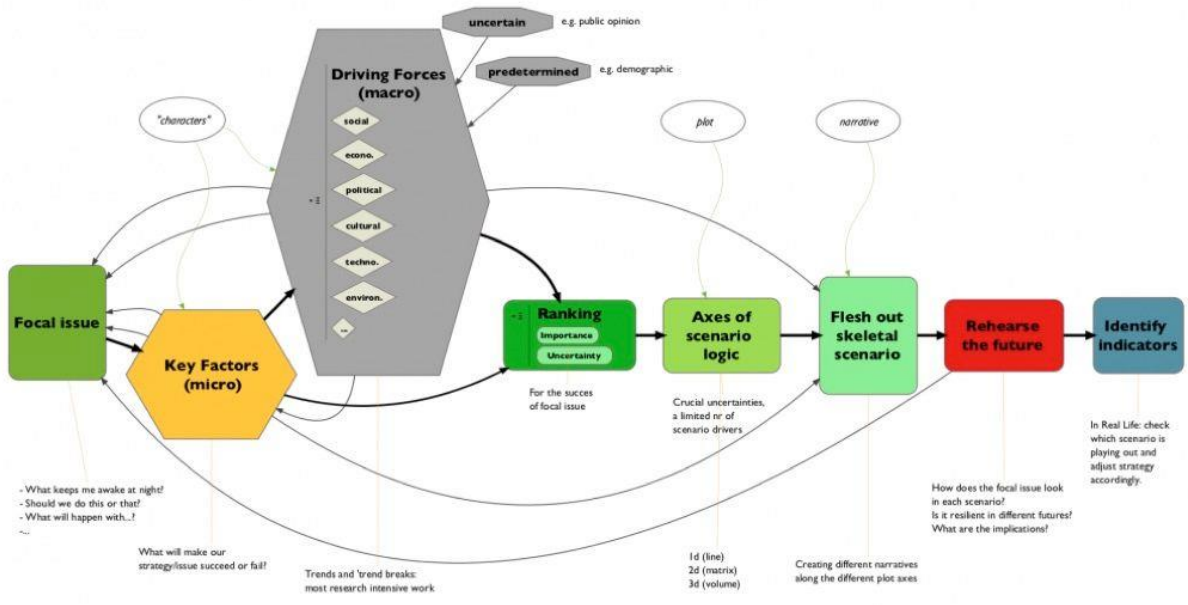


Figure A. 1 Steps to developing scenarios (Source: Schwartz 1991)

Steps used in this research are:

- Step 1: Focus Definition

The first step sets the foundation for further phases, including the definition of the focused question, desired outcomes, time frame, assumptions, stakeholder analysis and other preparation work. Here, the focus should be consistent with the research scope which contains two parts, one is physical and digital infrastructure and another one is SAE Level 4 automated driving.

- Step 2: Key Factors and Driving Forces Identification

After the whole picture of the issue is established, the next step is to assess a wide range of influence factors of unfolding events related to the issue. In this step, open thinking, diverse information resources and imagination are essential (Harris, 2014). To ensure this step is thorough, these following aspects need to be concerned: political, economic, societal, technological, legal and industry trends (Shoemaker, 1995).

Results from the previous workshop regarding automated driving and infrastructure; influence factors and drivers of others kinds infrastructure implementation or expansion, including ITC, e-government and information/intelligent infrastructure. Table A.1 lists those key factors and driving forces.

Table A. 1 Key factors and driving forces

Key Factors	Driving Forces
Public /Private expenditure	Policies, Economy, Market and Competition
Government support	Policies, Economy, Stakeholders' attitude
Governance mode	Policies, Stakeholders' attitude, Market and Competition
Social equity	Policies, Stakeholders' attitude
AV technology trails	Technology, Policies
Interoperability among AV technologies	Technology, Policies
Development of AV in EU	Technology, Policies, Stakeholders' attitude
Stability of policies	Policies
Emphasis in AV development	Policies, Stakeholders' attitude
Drivers' behavior	Policies, Stakeholders' attitude
Land use plan	Policies, Environment
Research and technical education trends	Technology, Economy, Stakeholders' attitude
Time urgency	Technology, Market and Competition
Current infrastructure condition	Environment
Safety requirements	Policies, Environment

- Step 3: Impact and Uncertainty Analysis

Considering the impact and uncertainty of each driving force, a ranking matrix can be used to assess those forces and narrow the list of forces to the most relevant for differentiating scenarios (Maack, 2001). Figure A.2 will be an example of this kind of matrix.

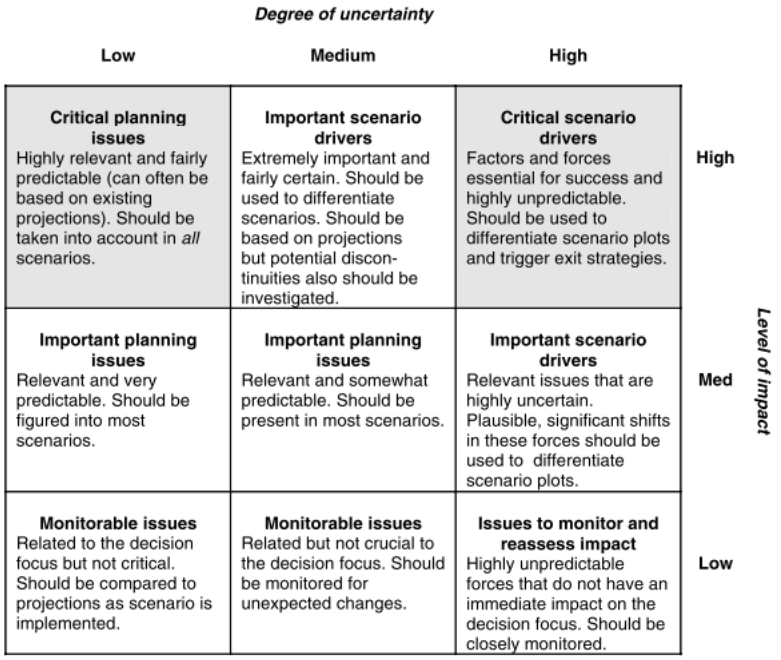


Figure A. 2 An example of impact/uncertainty matrix (Source: Maack, 2001)

Driving forces of Step 2 are analyzed in the aspects of their impacts on the research focus and their uncertainties in the future. The result is illustrated in Table A.2.

Table A. 2 Results of impact and uncertainty analysis

Driving force	Degree of uncertainty	Level of impact	Critical driver
Policies	High	Moderate	No
Economy	**High**	**High**	**Yes**
Market and competition	Moderate	Low	No
Stakeholders' attitude	**High**	**High**	**Yes**
Technology	Moderate	High	No
Environment	Low	Low	No

- Step 4: Scenario Building

Once two top driving forces are identified, ingredients for scenario construction are obtained. A widely used tool is a two-by-two matrix formed with the two major driving forces (Harris, 2014).

With this matrix, four scenarios are built, containing the most positive scenario and the most negative scenario.

According to the outcome of Step 3, economy and stakeholders' attitudes are the top two driving forces. The scenario matrix is built by public expenditure and cooperation among stakeholders. The matrix is in Figure 5.1.

- Step 5: Scenario Validation

Scenarios selected in the last step still need to be validated, regarding the characteristics of a good scenario plot: scenarios should be plausible, distinctive, consistent, relevant, creative, and challenging (Maack, 2001; Townsend, 2014).

This is finished during the interviews with stakeholders.

Appendix B
Autonomous Vehicles' Disengagement Report Analysis

External Condition	*Poorly marked lanes*	*121*	*42.91 %*	*4.63 %*
	Construction zone	*58*	*20.57 %*	*2.22 %*
	Heavy pedestrian traffic	*53*	*18.79 %*	*2.03 %*
	Weather condition	*18*	*6.38 %*	*0.69 %*
	*Other external condition factors***	*32*	*11.34 %*	*1.22 %*
	Total	***282***	***100 %***	***10.79 %***

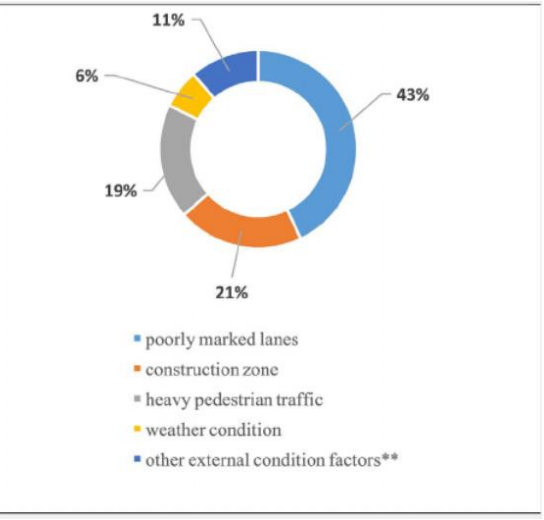


Figure B. 2 External Causes of Disengagement (Source: Favarò et al., 2018)

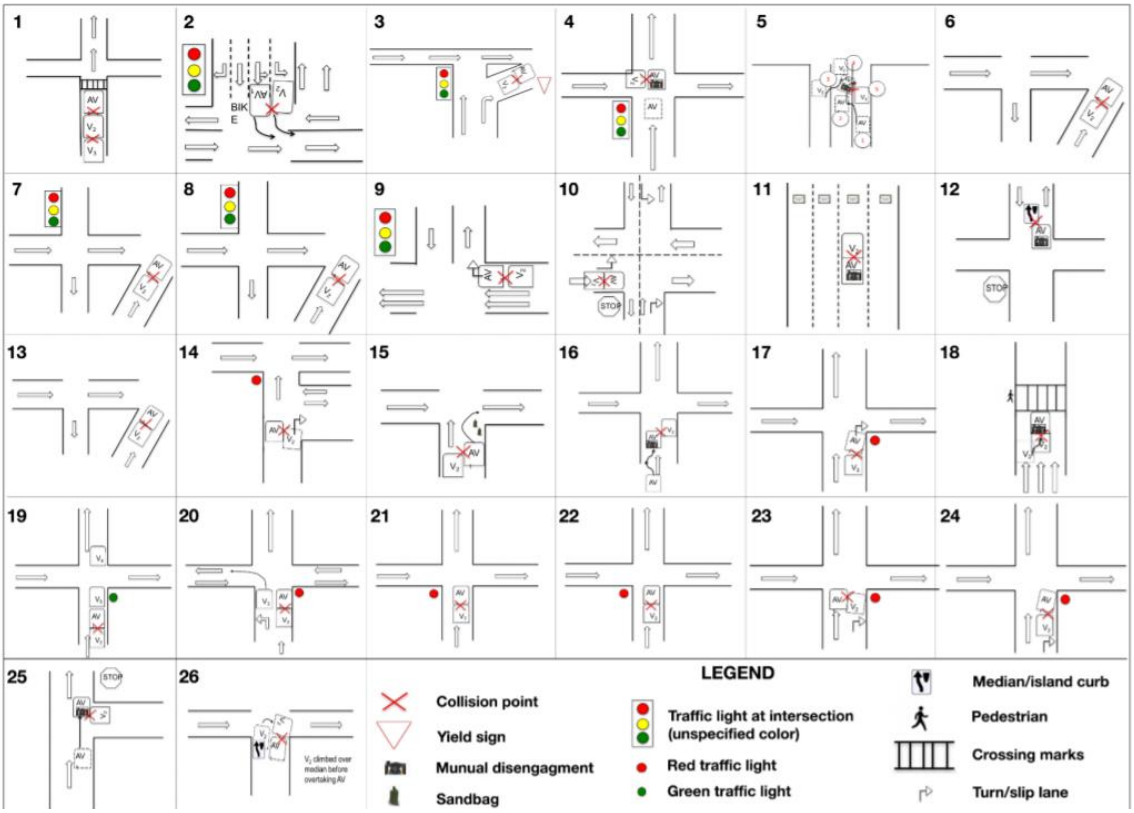


Figure B. 1 Accidents Overview (Source: Favarò et al., 2018)

Appendix C

Vehicles' Environment Perception Technology

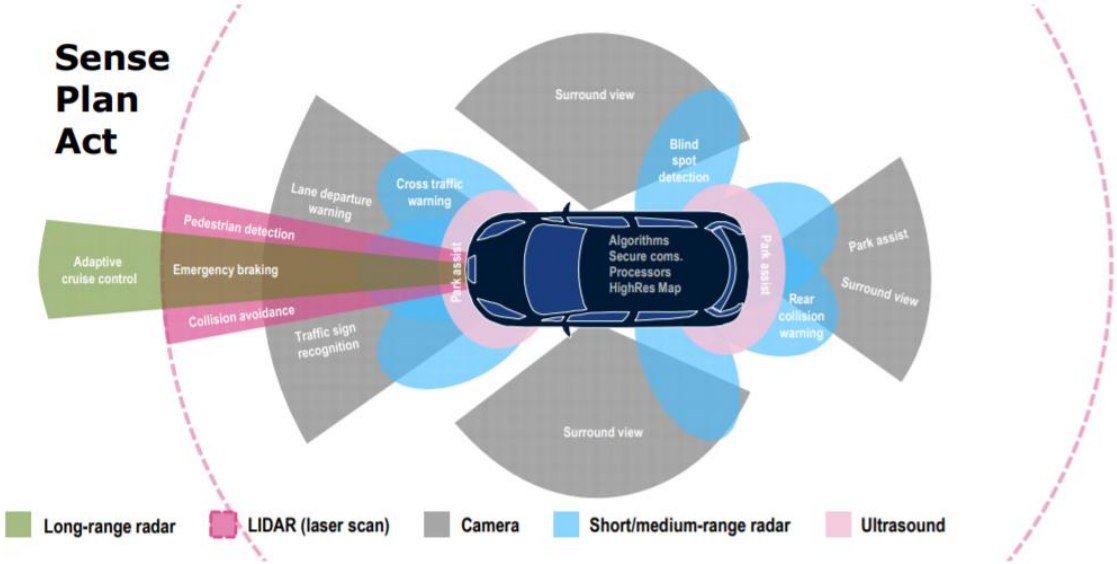


Figure C. 1 Technologies that allow vehicles to sense, plan and act in response to the dynamic driving environment (Souce: Parrish, 2015)

Appendix D

Interview Protocol (First Round)

Interview Protocol (First Round)

Infrastructure Requirements for Automated Driving

Delft University of Technology

INSTRUCTIONS

First of all, thank you for participating in this interview. I want to interview you because of your rich experience and expertise in relation to automated driving and road infrastructure. My research focuses on investigating potential infrastructure requirements for SAE Level4 vehicle automation regarding different future scenarios. A Level 4 car can handle most normal driving tasks on its own, but will still require driver intervention from time to time, during poor weather conditions, for example, or other unusual environments. Level 4 cars will generally do the driving for you, but will still have a steering wheel and pedals for a human driver to take over when needed.

Based on several researchers and manufacturers' work that high automation Level vehicles probably will be driving on the streets and highways within the next decades. Our road infrastructure needs upgrades to deal with the integration of automated vehicles while these upgrade requirements have not been clearly defined. Manufacturers and road authorities do have their own solutions, therefore, the start point of my research is to collect and analyze opinions from different relevant parties. Both physical and digital infrastructure will be involved and my research objectives are Dutch motorways and provincial roads.

This interview involves two parts.

i. *The first part is about open questions, in which I will ask you for your opinions and thoughts on infrastructure requirements for automated driving. The purpose is to get your perceptions on this issue and explore infrastructure requirements in addition to those from literature. There are no right or wrong or desirable or undesirable answers. I would like you to feel comfortable with saying what you really think and how you really feel.*
ii. *In the second part, I will show you some specific road situations and I will ask you about the infrastructure requirements in these specific situations.*

Interview Section 1 Open Questions

Q1 Could you please tell me something about your experience with the research and development of automated driving? And how do you regard the future application of SAE Level 4 automated vehicles?

- What are the relevance of your work content and automated driving? How many years have you worked on it?
- How do you regard the future application of SAE Level 4 automated vehicles? How fast will it go? Will it become a popular travel modal for normal citizens?
- Can they drive in mixed traffic or only on specific roads or dedicated lanes?

Q2 Automated driving involves a lot of advanced and innovative technologies and is developing rapidly. While infrastructure construction is a relatively traditional industry with lower development speed. Considering this, what do you think about the future roadmap of infrastructure with automated vehicles? Is it necessary to upgrade road infrastructure for automated driving?

- If yes, which infrastructure need upgrades? And when should these upgrades be finished?

Q3 When the road authority (transport agency) need to make decisions among alternatives of upgrading current infrastructure for automated vehicles, what advice will you give them? Which influencing factors need to be taken into account?

Q4 Could you please tell me something about your test with automated vehicles? (Which kind of vehicle? When? Where?)

- What are the reasons for choosing the test road?
- Do you add some roadside felicities or change some road infrastructure for the tests?

Interview Section 2 Requirements under Specific Road Situations

- In this section, please write down possible infrastructure requirements for automated driving under those road situations based on your experience.

Motorway-Straight segment

Infrastructure Requirements:

Motorway-Curve segment

Infrastructure Requirements:

Motorway-Weaving area

Infrastructure Requirements:

Motorway-Entrance & Exit

Infrastructure Requirements:

Provincial road-Unsignalized intersection

Infrastructure Requirements:

Provincial road-Signalized intersection

Infrastructure Requirements:

Provincial road-Roundabout

Infrastructure Requirements:

_____ _____

_____ _____

Provincial road-Roundabout with bicycle lane

Infrastructure Requirements:

_____ _____

_____ _____

Appendix E
Coding Process of the First Round Interviews

Step 1 Open coding

Interview transcripts were read a second time in a more thorough way. No category is defined before reviewing them. Every piece of information that may be useful and essential for this research is coded. This resulted in 203 open codes (See Figure E.1).

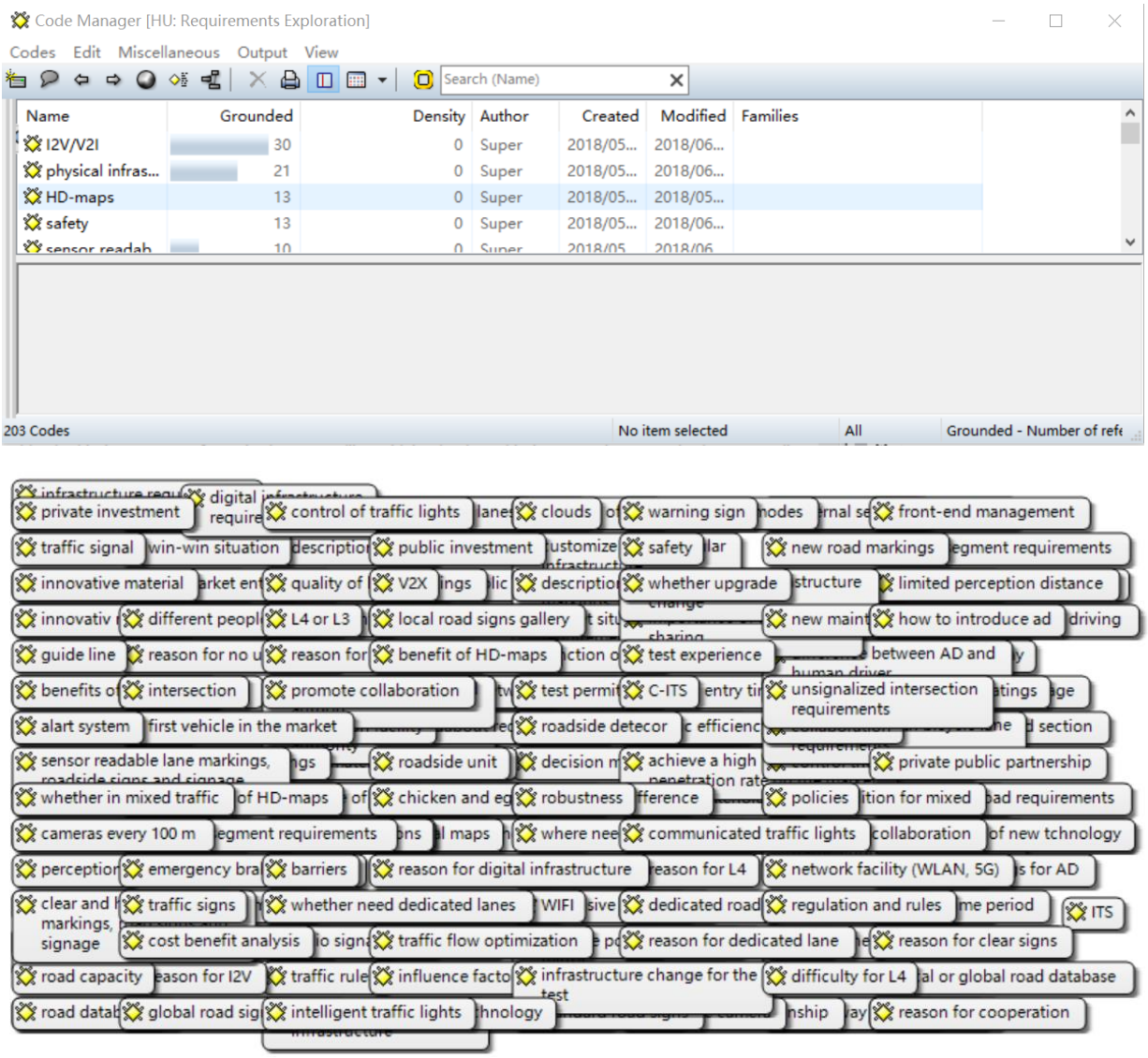
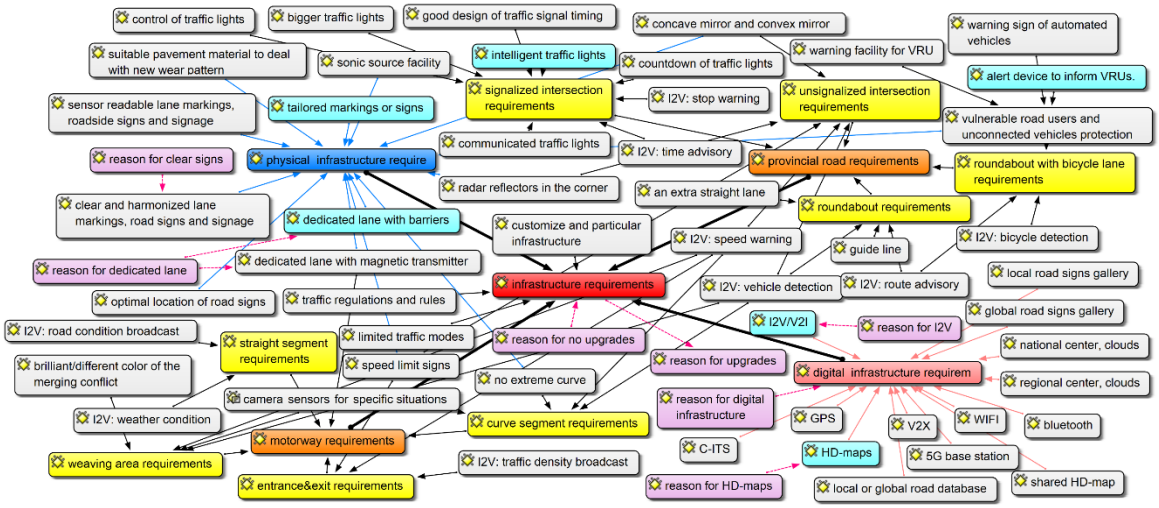
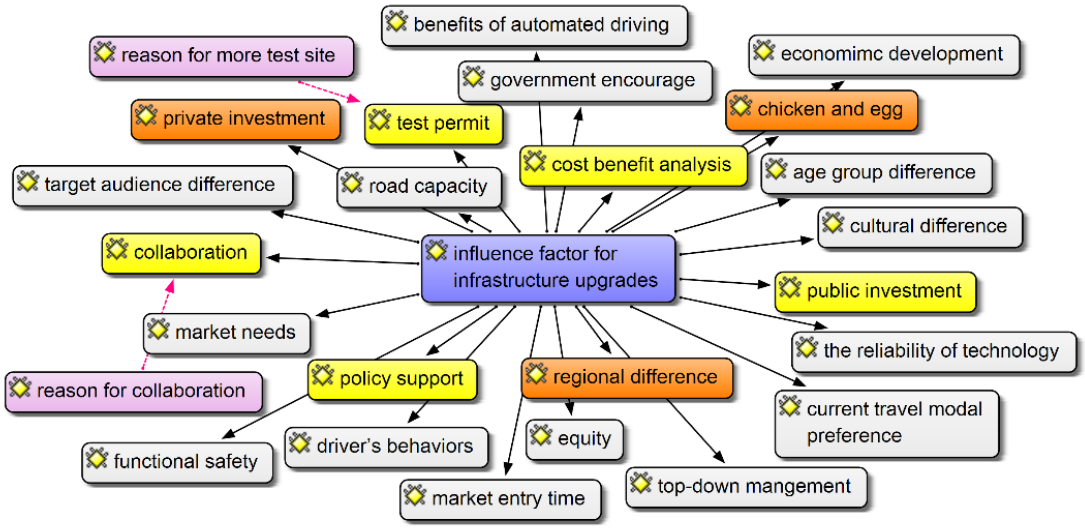


Figure E. 1 Open coding results (First round)

Step 2 Axial coding

After open coding, axial coding is applied. In this stage, the code system was organized, and some categories were either removed or downgraded into subcategories. By conducting the process several times, three main categories of those codes were built, as depicted in Figure E.2.





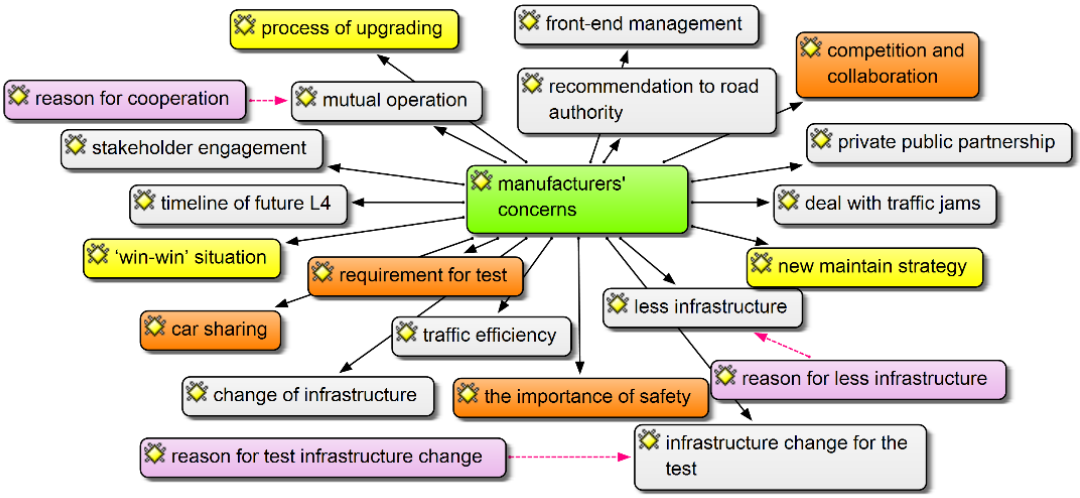


Figure E. 2 Axial coding results (First round)

Step 3 Selective coding

Finally following the axial coding, the selective coding was performed. One category (Infrastructure requirements) was selected as the core category (See Figure E.3).

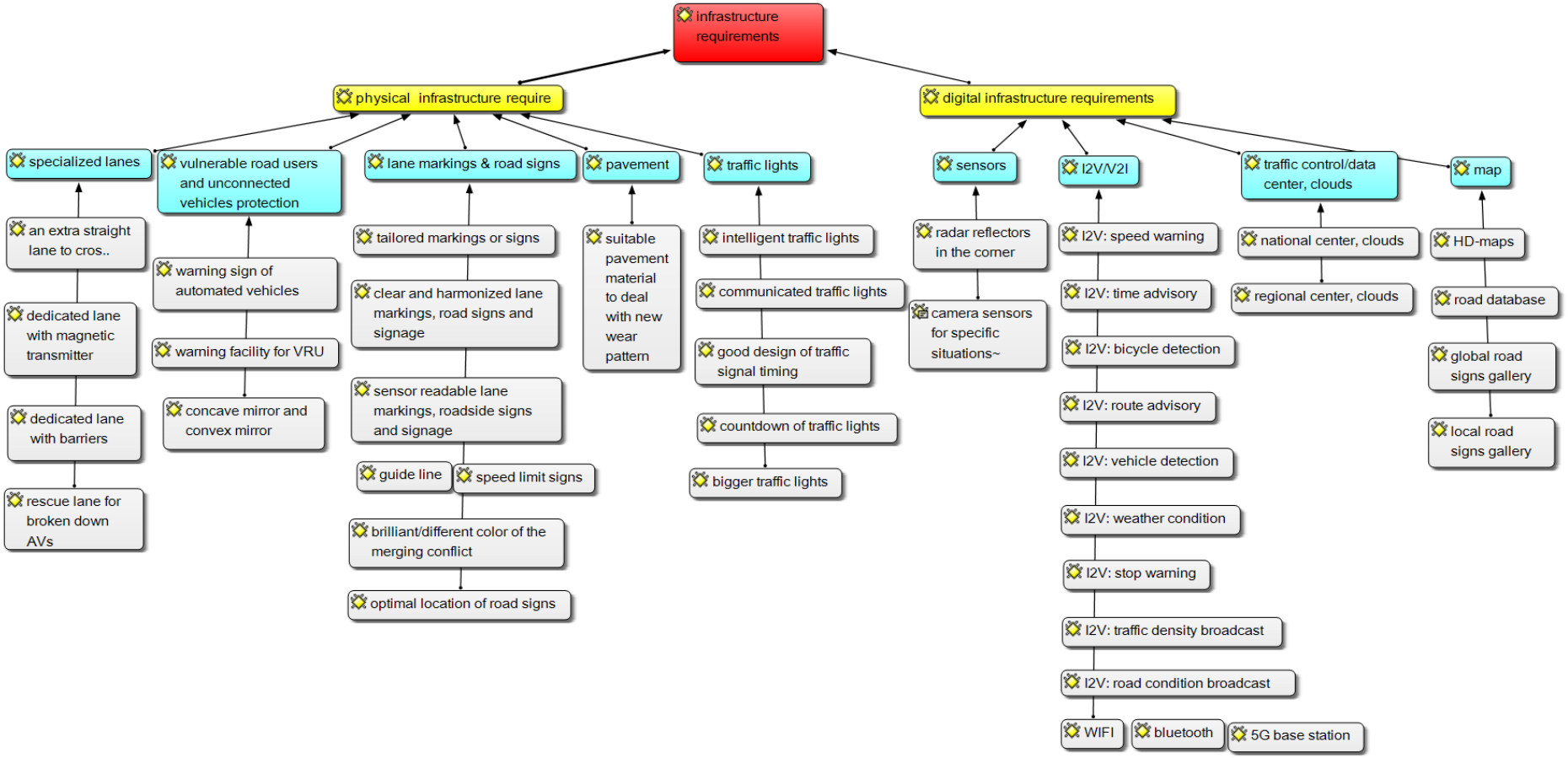


Figure E. 3 Selective coding results (First round)

Appendix F

Interview Protocol (Second Round)

Interview Protocol

Infrastructure Requirements for Automated Driving

Delft University of Technology

INSTRUCTIONS

First of all, thank you for participating in this interview. I want to interview you because of your rich experience and expertise in relation to automated driving and road infrastructure. My research focuses on investigating potential infrastructure requirements for SAE Level4 vehicle automation regarding different future scenarios. For a Level 4 vehicle, the sustained and Operational Design Domain-specific performance by an Automated Driving System of the entire Dynamic Driving Task and its fallback, without any expectation that a user will respond to a request to intervene. Level 4 cars will generally do the driving for you, but will still have a steering wheel and pedals for a human driver to take over when needed.

Based on several researchers and manufacturers' work that high automation Level vehicles probably will be driving on the streets and highways within the next decades. Our road infrastructure might need upgrades to deal with the integration of automated vehicles while these upgrade requirements have not been clearly defined. Manufacturers and road authorities do have their own solutions, therefore, the start point of my research is to collect and analyze opinions from different relevant parties and then map those requirements into different future scenarios regarding the feasibility and impacts. Both physical and digital infrastructure will be involved and my research scope is Dutch motorways and provincial roads.

This interview involves two parts.

iii. *The first part is about open questions, in which I will ask you for your opinions and thoughts on infrastructure requirements for automated driving. The purpose is to get your perceptions on this issue and explore infrastructure requirements in addition to those from literature.*

iv. *In the second part, I will show you four possible future scenarios of infrastructure and automated driving, together with manufacturers' requirements for infrastructure under several specific road situations. You can assess those requirements based on your knowledge and add new requirements which are not included as well.*

Interview Section 1 Open Questions

Q1 Could you please tell me something about your experience with the research and development of automated driving? And how do you regard the future application of SAE Level 4 automated vehicles?

- What are the relevance of your work content and automated driving? How many years have you worked on it?
- How do you regard the future application of SAE Level 4 automated vehicles? What is the timeline? How fast will it go? Will it become a popular travel modal for normal citizens?
- Can they drive in mixed traffic or only on specific roads or dedicated lanes?

Q2 Is it necessary to upgrade road infrastructure for automated driving?

- If yes, why do you think so?
- How do you see the investment in this issue? Do you think all physical infrastructure should be invested by the road authority? And private parties work on digital infrastructure? (Is there any possible business model for this investment?)

⋆ (depend on available time)

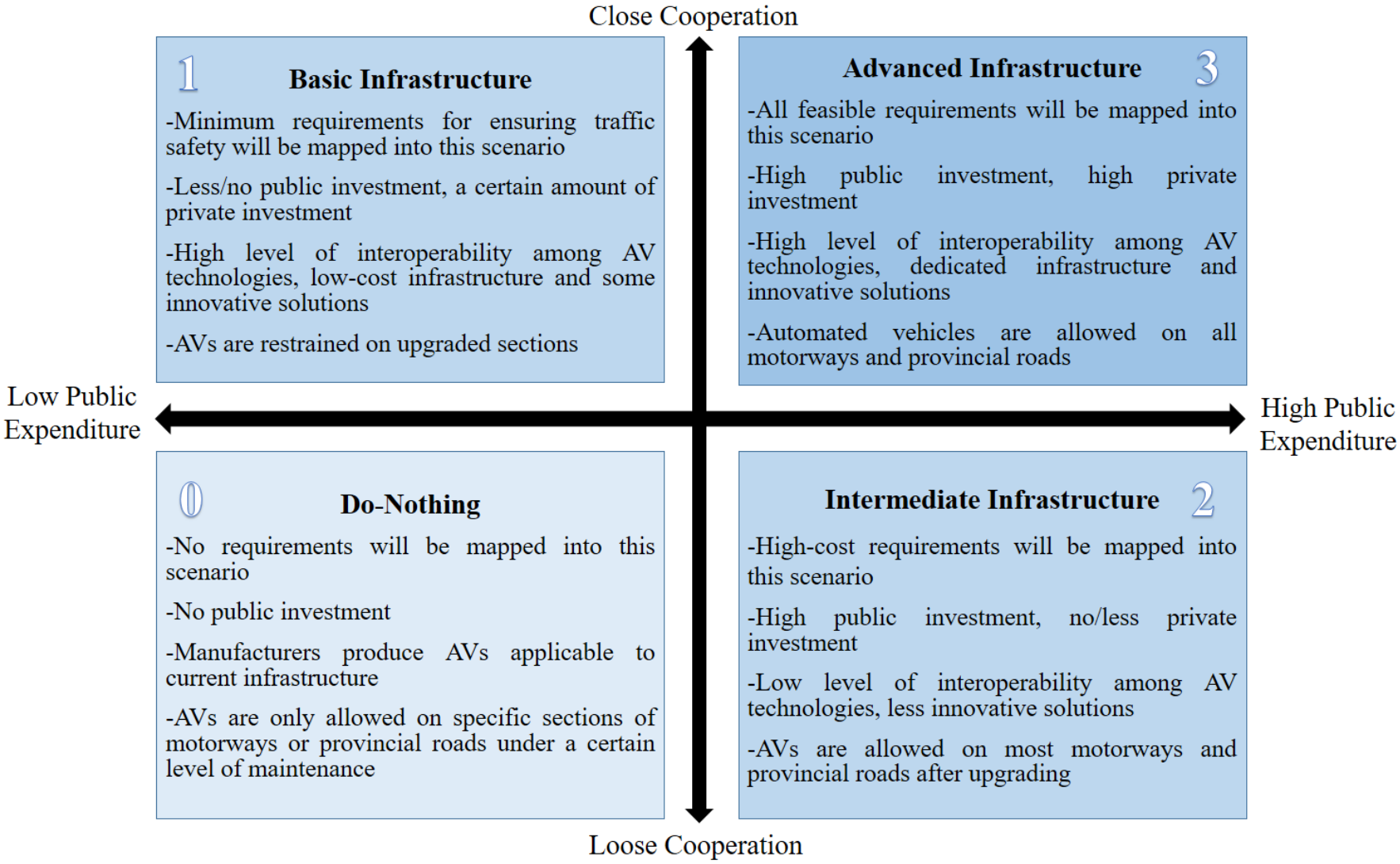
- (Should these upgrades be finished before public roads are open for automated vehicles or we should first introduce these vehicles to the roads?
- How do you see the role of your organization in the process of upgrading infrastructure for automated driving?)

⋆ (depend on available time) Q3 When you need to make decisions among alternatives of upgrading current infrastructure for automated vehicles, which influencing factors will you take into account or which assessing criteria will you use?

When the road authority need to make decisions among alternatives of upgrading current infrastructure for automated vehicles, could you please give some suggestions to them? Which assessing criteria should they use?

- You can consider those factors:
  Stakeholders' attitude: good collaboration and communication among stakeholders
  Economy: Public /Private Expenditure
  Policy: Social equity
  Technology: Interoperability among AV technologies
  Environment: Current infrastructure condition

Q4 Here are four scenarios for the future of automated driving and infrastructure. Which one do you think that will happen in the future and why? Is there any other possible scenario?


Close Cooperation
1
Basic Infrastructure
-Minimum requirements for ensuring traffic safety will be mapped into this scenario
-Less/no public investment, a certain amount of private investment
-High level of interoperability among AV technologies, low-cost infrastructure and some innovative solutions
-AVs are restrained on upgraded sections
3
Advanced Infrastructure
-All feasible requirements will be mapped into this scenario
-High public investment, high private investment
-High level of interoperability among AV technologies, dedicated infrastructure and innovative solutions
-Automated vehicles are allowed on all motorways and provincial roads
Low Public Expenditure
High Public Expenditure
0
Do-Nothing
-No requirements will be mapped into this scenario
-No public investment
-Manufacturers produce AVs applicable to current infrastructure
-AVs are only allowed on specific sections of motorways or provincial roads under a certain level of maintenance
2
Intermediate Infrastructure
-High-cost requirements will be mapped into this scenario
-High public investment, no/less private investment
-Low level of interoperability among AV technologies, less innovative solutions
-AVs are allowed on most motorways and provincial roads after upgrading
Loose Cooperation

Interview Section 2 Requirements under Future Scenarios

- In this section, please choose possible infrastructure requirements for automated driving from the list for these different future scenarios.

Infrastructure Requirements			Scenario 1: Basic	Scenario 2: Intermediate	Scenario 3 Advanced
Physical	Specialized lanes	Dedicated lane with barriers			
		Dedicated lane with magnetic transmitter			
		An extra straight lane for AVs to cross the roundabout			
		Rescue lane for broken down AVs			
	Lane markings & Road signs	Clear and harmonized lane markings, road signs			
		Sensor readable lane markings, road signs			
		Tailored signs or markings for automated vehicle			
		Loop signs in the curve segment of motorway			
		Brilliant/different color of the merging conflict			
		Speed limit signs for intersections, entrances and exits of motorways			
		Guide marking or road signs for automated vehicle in the roundabout			
		Warning signs for vulnerable road users			
		Remove road signs to the road surface			
		Optimal location of road signs			
	Traffic lights	Good design of traffic signal timing			
		More visible (bigger) traffic lights			
		Countdown for traffic lights			
		Communicated traffic lights			
		Intelligent traffic lights with flexible timing			
	Vulnerable road users and unconnected vehicles protection	Alert device to inform VRUs.			
		Isolating facilities			
		Concave mirror and convex mirror at the unsignalized intersection			
	Pavement	Suitable pavement material to deal with new wear pattern			

Digital	Map	HD-maps			
		Road database			
		Global road signs and lane markings gallery			
		National road signs and lane markings gallery			
	Sensors	Camera sensors for specific situations			
		Radar reflectors in the corner			
	Traffic control/data center, clouds	National center, clouds			
		Regional center, clouds			
		Global clouds			
	I2V/V2I	Straight segment: weather condition and road condition broadcast			
		Curve segment: speed warning and vehicle detection			
		Weaving area: speed warning and vehicle detection			
		Entrance&Exit: speed warning, traffic density broadcast			
		Unsignalized intersection: speed warning and vehicle detection			
		Signalized intersection: time advisory, stop warning			
		Roundabout: route advisory, vehicle detection			
		Roundabout with bicycle lane: route advisory, vehicle and bicycle detection			
		5G base station			
		WIFI			

Appendix G

Experts Opinions on Requirements Mapping

Table G. 1 Statistics results of requirements mapping

Infrastructure Requirements			Scenario 1								Scenario 3							
			8#	9#	10#	11#	12#	13#	14#	Total	8#	9#	10#	11#	12#	13#	14#	Total
P	Specialized lanes	Dedicated lane with barriers			✔	✔				2	✔		✔		✔	✔		4
h		Dedicated lane with magnetic transmitter				✔	✔			2	✔		✔	✔	✔	✔		5
y		An extra straight lane for AVs to cross the roundabout			✔	✔				2	✔		✔		✔			3
s		Rescue lane for broken down AVs	✔				✔			2		✔	✔		✔	✔		4
I	Lane markings & Road signs	Clear and harmonized lane markings, road signs	✔	✔	✔	✔		✔	✔	6	✔		✔	✔	✔	✔		5
c		Sensor readable lane markings, road signs		✔						1	✔	✔	✔	✔	✔	✔	✔	7
a		Tailored signs or markings for automated vehicle		✔						1	✔		✔	✔	✔	✔	✔	6
L		Loop signs in the curve segment of motorway	✔		✔	✔				3			✔		✔	✔		3
		Brilliant/different color of the merging conflict								0	✔		✔	✔	✔			4
		Speed limit signs for intersections, entrances and exits of motorways	✔	✔	✔	✔		✔	✔	6	✔	✔	✔			✔	✔	5
		Guide marking or road signs for automated vehicle in the roundabout			✔	✔			✔	3	✔	✔	✔		✔	✔	✔	6
		Warning signs for vulnerable road users	✔	✔	✔	✔				4	✔		✔		✔		✔	4
		Remove road signs to the road surface			✔					1	✔	✔	✔	✔	✔			5
		Optimal location of road signs	✔	✔	✔	✔	✔			5			✔		✔	✔	✔	4
	Traffic lights	Good design of traffic signal timing	✔	✔		✔				3			✔		✔	✔		3
		More visible (bigger) traffic lights			✔	✔				2	✔		✔		✔			3
		Countdown for traffic lights	✔		✔					2	✔		✔	✔	✔	✔		5
		Communicated traffic lights	✔		✔					2	✔	✔	✔	✔	✔		✔	6
		Intelligent traffic lights with flexible timing	✔	✔						2	✔	✔	✔	✔	✔	✔	✔	7
	Vulnerable road users and unconnected vehicles protection	Alert device to inform VRUs.	✔			✔				2	✔	✔	✔		✔	✔	✔	6
		Isolating facilities	✔		✔	✔				3			✔		✔	✔		3
		Concave mirror and convex mirror at the unsignalized intersection	✔		✔					2			✔		✔	✔		3
	Pavement	Suitable pavement material to deal with new wear pattern		✔						1			✔	✔	✔	✔	✔	5

Infrastructure Requirements			Scenario 1								Scenario 3							
			8#	9#	10#	11#	12#	13#	14#	Total	8#	9#	10#	11#	12#	13#	14#	Total
Digital	Map	HD-maps	✔		✔	✔	✔	✔		5	✔	✔	✔	✔	✔	✔	✔	7
		Road database	✔		✔	✔		✔	✔	5	✔	✔	✔	✔	✔	✔	✔	7
		Global road signs and lane markings gallery	✔		✔	✔		✔	✔	5	✔	✔	✔	✔	✔	✔	✔	7
		National road signs and lane markings gallery	✔	✔	✔	✔		✔		5	✔	✔	✔		✔	✔		6
Tal	Sensors	Camera sensors for specific situations		✔						1			✔	✔	✔	✔	✔	5
		Radar reflectors in the corner	✔	✔						2			✔	✔	✔	✔	✔	5
	Traffic control/data center, clouds	National center, clouds	✔					✔		2			✔	✔	✔			4
		Regional center, clouds	✔					✔		2			✔	✔	✔		✔	4
		Global clouds								0	✔			✔		✔		3
	I2V/V2I	Straight segment: weather condition and road condition broadcast	✔		✔	✔	✔	✔		5			✔	✔	✔	✔	✔	5
		Curve segment: speed warning and vehicle detection	✔		✔	✔		✔		4			✔		✔	✔	✔	4
		Weaving area: speed warning and vehicle detection	✔		✔	✔		✔		4			✔		✔	✔	✔	4
		Entrance&Exit: speed warning, traffic density broadcast	✔		✔	✔		✔		4			✔		✔	✔	✔	4
		Unsignalized intersection: speed warning and vehicle detection	✔		✔	✔		✔		4			✔	✔	✔	✔	✔	5
		Signalized intersection: time advisory, stop warning	✔		✔			✔		3			✔	✔	✔	✔	✔	5
		Roundabout: route advisory, vehicle detection	✔		✔		✔			3			✔	✔	✔	✔	✔	5
		Roundabout with bicycle lane: route advisory, vehicle and bicycle detection	✔		✔	✔		✔		4			✔	✔	✔	✔	✔	5
		5G base station		✔	✔	✔		✔	✔	5			✔	✔	✔	✔	✔	5
		WIFI		✔	✔	✔		✔	✔	5			✔	✔	✔	✔	✔	5
		Blue tooth		✔	✔	✔		✔	✔	5			✔	✔	✔	✔	✔	5

Appendix H

Coding Process of the Second Round Interviews

The coding process applied here is the same as it in Chapter 6, starting from open coding, then axial coding and ending with selective coding. Results of these three steps are shown in Figure G.1 to Figure G.3.

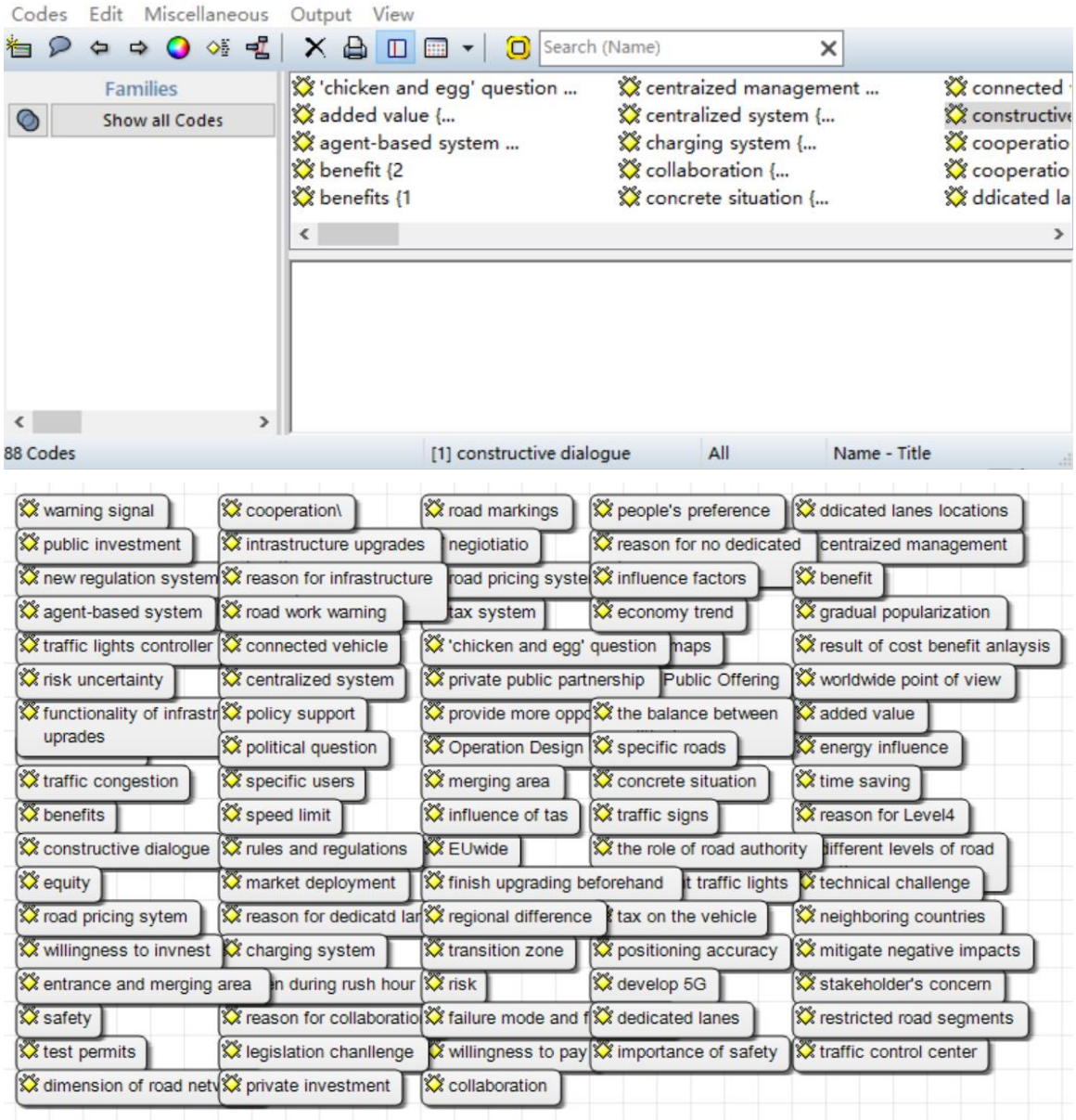


Figure H. 1 Open coding results (Second round)

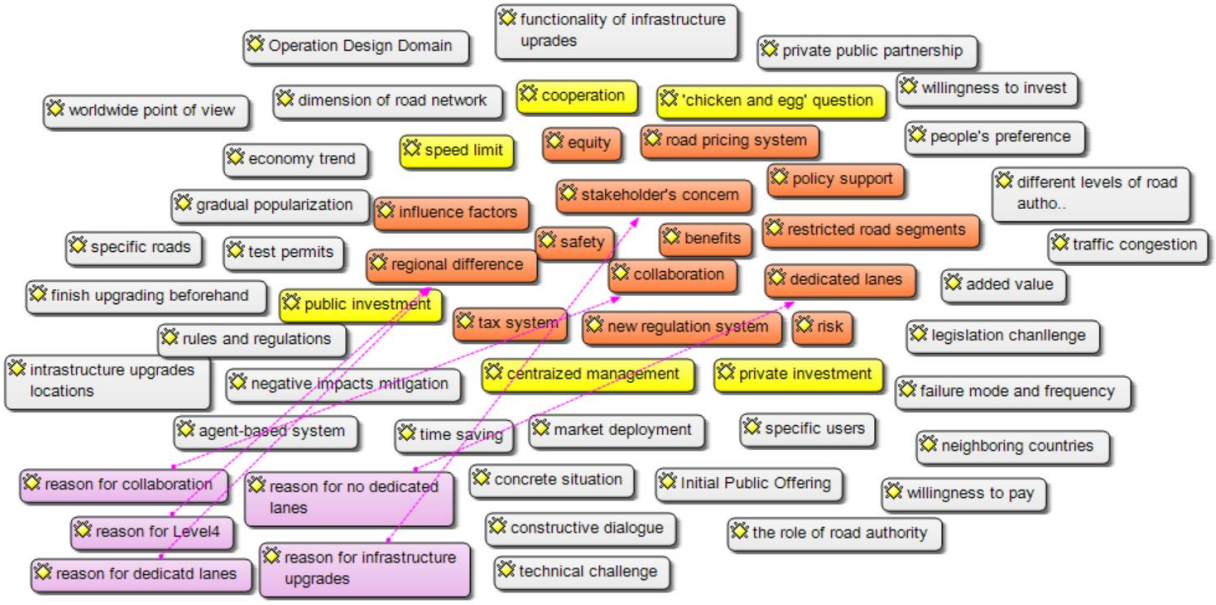


Figure H. 2 Axial coding results (Second round)

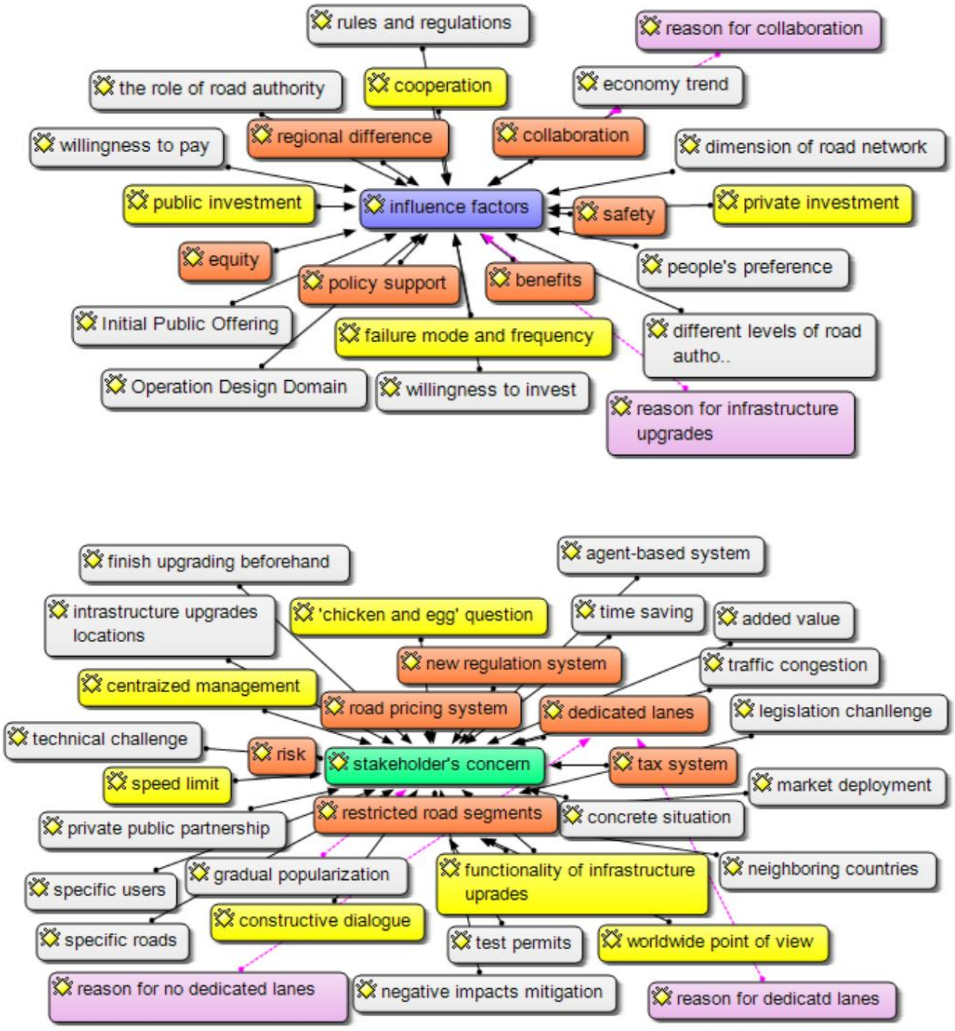


Figure H. 3 Selective coding result (Second round)

Master Thesis

Author: X. (Xiaolin) LU

Construction Management & Engineering
Faculty of Civil Engineering and Geosciences

Delft