TrafficQuest

CENTRE FOR EXPERTISE ON TRAFFIC MANAGEMENT

TrafficQuest report

Car Dependency and Traffic Management

What to expect in the era of automated driving?

Colophon

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Date	January 31st, 2025
Version	1.0
Published by	TrafficQuest P.O. Bos 2232 3500 GE UTRECHT

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TNO innovation for life · TU Delft · Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat

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Preface

This year's TrafficQuest challenge focused on the combination of automated driving and car dependency, and automated driving and traffic management. Even though these topics on their own could justify a separate TrafficQuest challenge, the project team experienced during the project that the topics are very much intertwined. Especially when discussing the potential future scenarios, we were reminded that one cannot ignore either the effects of automated driving on traffic management or the systemic effects on car dependency. Combining these topics helped to better understand the potential implications of different future scenarios and showed the importance of researching these topics and potential policy implications. This resulted in interesting discussions, both within the project team and with the interviewees. We would like to thank everyone involved for their valuable contributions.

The TrafficQuest team,

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January, 2024

1 Introduction

Automated driving (see definition in section 2.3) is expected to play an important role in our future mobility system. Self-driving vehicles are already on the road in various places around the world. For example, there are already self-driving taxis in the United States and self-driving shuttles have also been running in the Netherlands for years. Although it is not clear yet whether automated driving will be rolled out only for shared mobility or for private use or both, several studies show that this is likely to lead to an increase in car use (Lehtonen et al, 2022; Hardman, 2021) and perhaps indirectly to an increase in car dependency – the combination of subjective and objective factors that determine to what extent an individual is dependent on the car as transportation mode. Regardless of the form in which automated vehicles are eventually rolled out in the future, the impact of automated driving on car dependency and on traffic management needs to be thoroughly examined. For example, it is expected that automated vehicles could become relatively affordable leading to increased ownership and more vehicle kilometres being driven. In addition, it is expected that in the future, high value of travel time (VOT) will be partially compensated (reduced) by being able to be productive while driving. This advantage of productivity during a trip is expected to make automated vehicles an attractive mode of travel as they could offer people an opportunity to use their travel time in a more pleasant and productive manner compared to manually driven vehicles (Chidress et al 2015; Cornet et al 2021). If in the future the use of automated vehicles becomes the norm and more vehicle-kilometres are driven with these types of vehicles, then traffic management strategies and policies will have to be redefined to accommodate the new reality on the road. These expected changes underline the need to carefully consider wider implications for the mobility system and policy goals when rolling out automated driving. This TrafficQuest challenge was conducted to investigate this.

TrafficQuest was the partnership between Rijkswaterstaat, TNO, and TU Delft in the field of traffic management and traffic information. From 2009 to 2016, this cooperation was active in developing, accumulating, applying, and disseminating knowledge about traffic management and traffic information. For more than seven years, TrafficQuest covered the entire field, from the more fundamental, theoretical knowledge about traffic management and traffic information to 'operational knowledge' about its application and effectiveness. At the end of 2016, the decision was made to continue on a smaller scale, concentrating activities on a number of current challenges and on the publication of Verkeer in Nederland ('Traffic in the Netherlands'). This annual publication gives an overview of how traffic is currently being managed in the Netherlands and developments in traffic management.

A challenge is a quick-scan expert analysis with a short lead time. TrafficQuest's challenges are intended to address and dive deeper into specific topics related to traffic management. Over the past years, challenges have been conducted on the replacement of roadside systems by in-car systems, traffic management and traffic safety, the impact of C-ITS use cases, 3D printing, traffic management and AI, and traffic management and broad prosperity.

1.1 Goal and scope of this challenge

A future with more automated vehicles in cities contrasts with current policies of many cities whose goal is often to keep cars out in order to combat issues such as congestion and the corresponding need for new road construction or widening of existing roads; the allocation of (scarce) space for parking; the marginalization of alternative transportation modes (e.g., public transportation or active mobility); and increased transportation-related climate impacts. Therefore, it is necessary for relevant stakeholders to already start thinking now about measures that will enable their policy goals to be achieved in a future where automated driving becomes prevalent. The goal of this challenge is thus to perform a quick scan analysis of the expected effect of automated driving on car dependency and how to steer to reduce car dependency in a future with automated driving. In addition, we investigate the effects on, and the possibilities of, traffic management if automated driving becomes the norm.

The scope of the analysis is limited to hypothetical scenarios and assumptions of automated driving which are defined in the report. The main focus is to examine the relationship between automated driving and car dependency, and automated driving and traffic management. It does not thoroughly cover other important aspects of automated driving such as equity, transport poverty and traffic safety. Finally, we stress that this analysis is not intended to give a complete view of all possible effects but to provide policy makers and other relevant stakeholders a good starting point for a more in-depth analysis and discussions on the topic.

1.2 Research Questions

This research is split into two main topics to gain a better understanding of the relationship between automated driving, car dependency and traffic management. Each has its own research questions as defined below:

1. Automated driving and the change in car dependency
    a. What is car dependency? When do people experience car dependency and when do they actually depend on the car?
    b. How does automated driving influence the choice of alternatives to the (private) car and how does this change the degree of car dependency?
2. Automated driving and traffic management
    a. How will automated driving change traffic flow, the amount of passenger car kilometres driven and the accessibility of activities?
    b. What role can traffic management play in achieving policy goals in a context of automated driving? What is needed for this in terms of development, data, and organization?

1.3 Research Approach

To investigate how automated driving could change car dependency, we first answered the question of what car dependency is, making a distinction between subjective and objective car dependency using a quick-scan literature review. Furthermore, we analysed the role traffic management can play if automated driving becomes the norm. The knowledge gained from the literature review was further deepened and contextualized through interviews with experts in the field of car dependency, automated driving, and traffic management.

Based on the literature review and expert interviews, a causal loop diagram (CLD) was developed to analyse how car dependency could change when automated driving is present on a large scale. Three different scenarios were analysed to provide insights into the effect of automated driving on car dependency and traffic management. We looked at one scenario where automated driving is rolled out with privately owned vehicles, one scenario with shared automated vehicles for private rides (e.g. robo-taxis), and one scenario with shared automated vehicles for collective rides (e.g. automated buses). For each scenario, we analyse the factors that determine car dependency and the relationship between these factors. Within each scenario, we investigated to what extent the automated driving scenarios might result in changes in car dependency (increase or decrease) and to what extent they might have an effect on traffic management.

Chapter 2 contains the literature review and interviews on car dependency, the CLD, and the introduction of the three scenarios. In chapter 3, the topic of traffic management is discussed with again a literature review and an expert interview. The insights of both chapters are then combined in the scenario analysis in chapter 4. The conclusions drawn from this analysis are discussed in chapter 5.

2 Car Dependency and Automated Driving

This chapter focuses on car dependency and the influence automated driving can have on this concept (more in-depth literature about automated driving itself is part of chapter 3). First, Section 2.1 presents the result of a quick-scan literature review conducted on car dependency and its relation to automated driving. Then, Section 2.2 presents the findings from three expert interviews on this topic to further deepen the findings from literature. Concluding from this, section 2.3 presents some definitions and assumptions that are used in this research. In section 2.4, a causal loop diagram of car dependency and its related factors is presented. This causal loop diagram is then used to reflect on the various ways in which automated driving might impact different factors related to car dependency. This is described in section 2.5.

2.1 Literature Review

From 2019 to 2022, the passenger cars' share of passenger transport in the EU changed from 69.8% to 72.2%, reaching a peak during the Covid-19 pandemic years of 2020 (81.8%) and 2021 (80.3%) (Eurostat, 2024). The figures for the Netherlands show an even higher participation of passenger cars in the country's modal split for passenger transport (average of 5.6% above EU levels), as depicted in Figure 1.

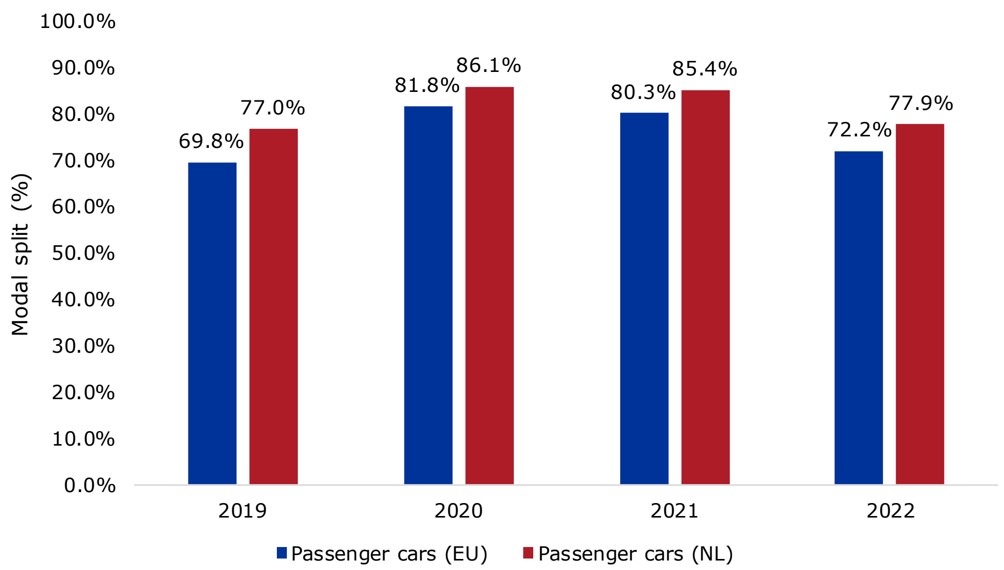


Figure 1. Modal split (in kms travelled) of passenger cars in passenger transport in EU and NL[1]

Excessive use of car for trips can lead to negative effects both for individuals as well as for the physical environment. For example, excessive car use can lead to more congestion, the need for increased road supply (via road construction or widening), allocation of (scarce) space for parking purposes, marginalisation of alternative transportation modes (e.g., public transportation or active mobility), urban sprawl, and increased transportation-related climate impacts. The excessive use of

[1] Source: Eurostat (online data code)

cars can also negatively affect individuals by causing impacts on mental health (e.g., stress related to being on traffic jams, traffic noise), physical health (e.g., reduced active mobility, traffic pollution), road accidents and injuries – especially for vulnerable road users – which accounted for nearly 70% of total fatalities in urban areas (Directorate-General for Mobility and Transport, 2024), among others.

The excessive use of car for transport can also lead to a phenomenon known as **car dependency**, which is one of the topics of this study. Car dependency is a complex issue with multiple components, and there is currently no uniquely agreed definition of it in scientific literature (Muñoz et al., 2024). Scientific and grey literature on car dependency point towards both **objective** and **subjective** factors associated with car dependency, as well as factors associated with **individuals**, **places**, and **trip purposes** impacting car dependency.

In a recent systematic literature review on car dependency, Muñoz et al. (2024) identified different "operationalisation trends" of car dependency (i.e., how the concept was understood):

1. **Car dependency as car use and ownership:** According to this classical view, metrics such as car ownership, number of work-related trips, average distance, frequency of car use, or car distance travelled are used to conceptualise car dependency. Muñoz et al. (2024) point out that these conceptualisations are the most widely accepted ones in literature.
2. **Car dependency as an accessibility outcome**: In this perspective, car dependency is exacerbated by accessibility issues. Metrics such as work commutes longer than feasible cycling distance can be used to conceptualise car dependency. According to this accessibility perspective, car dependency happens when transportation developments occur in a way that makes the car the "main mode of transport to access basic opportunities" (Langer et al., 2023, p.89).
3. **Car dependency as subjective perceptions**: Multiple subjective factors can also be associated with car dependency (or perceived car dependency). Some of these factors are investigated by Helferich et al. (2024) in the context of the Automobility Engagement (AE), a concept previously proposed to consumers perceptions and engagement with car ownership and use, including perceived car dependency, car identity, alternative travel norms, house ownership preferences, environmental concern, empowerment, and driving aversion. Surveys using Likert-type scales are usually used to investigate how much individuals agree (or disagree) with statements related to car use or ownership, such as "I need a car to fulfil my everyday obligations", "Sometimes I feel too dependent on my car", or "I feel in control when I am driving" (Helferich et al., 2024). Subjective factors associated with car dependency however can make it challenging to determine when a perceived reliance on using a car turns into an actual dependence on it (Lucas, 2009; Muñoz et al., 2024). This happens because the relationship between subjective perceptions of car dependency and objective factors (e.g., transport modes, environmental characteristics) is usually mentioned in literature but the causal relationships between them are not demonstrated (Muñoz et al., 2024).
4. **Car dependency as a modelling of choices**: This approach considers that an individual chooses a transport mode for a trip based on time and cost considerations of the available options. If the only possible choice for a trip is by means of a car, a person would then be considered as car dependent. One important limitation of this approach is that it considers trips that actually occur,

so factors that affect and limit participation of people in desired activities due to e.g. not having access to a car are not considered (Muñoz et al., 2024).

5. **Car dependency as an explanatory variable**: A final operationalisation trend mentioned by Muñoz et al. (2024, p.7) refers to car dependency as a "variable used to explain or construct another concept". Following this approach, car dependency can be used to investigate or better understand other things, such as attitudes of people towards transport policies or car-related innovations, obesity levels within specific user groups, among others, as discussed by the authors.

Based on the above, it becomes clear that car dependency is connected to more concrete and objective factors – such as car ownership, car usage, or accessibility – as well as to more subjective factors, such as perceived identity, empowerment, mobility habits. In this context, some relevant conceptualisations of car dependency identified in this literature review that take into account a holistic view of car dependency are presented below. These definitions are further used to propose (in section 2.3) the working definition of car dependency in the context of this report.

According to Muñoz et al. (2024), car dependency refers to the interplay of personal and contextual factors that favour car-based transportation over other travel and access alternatives. Weir et al. (2024, p.374) expand on this logic by stating that car dependency is the "interaction of political, economic, environmental, interpersonal, and individual factors that create a car-orientated society". It becomes clear that, according to these definitions, car dependency is the outcome of a complex interaction of both objective and subjective factors. Objective car dependency relates to a lack of alternatives to the car that are either viable in terms of cost, travel time, or convenience (Jeekel, 2013; as cited in Weir et al., 2024), or just not having acceptable alternatives to the car in terms of travel time and costs (Wiersma et al., 2015). Subjective car dependency, on the other hand, considers also individual habits and a culture of car use, with a lack of knowledge or interest in alternative modes of transport (Jeekel, 2013, as cited in Weir et al., 2024).

The relation between car dependency and automated driving was also explored in this literature review. However, the intersection of these two topics seemed to be a gap in existing knowledge since very limited literature was available. Therefore, this report aims to make some first steps in filling this gap by combining literature on car dependency with literature on automated driving and traffic management (see also the literature review on traffic management in section 3.1) and then substantiating this with expert interviews and a scenario analysis using a causal loop diagram (see section 2.5 and chapter 4).

2.2 Expert Interviews

In addition to the quick-scan literature review, more insights in car dependency and its relation to automated driving were gained by interviewing three experts in this field.

- Toon Zijlstra is a researcher at the Netherlands Institute for Transport Policy Analysis (KiM) and co-author of the 2022 KiM report on car dependency 'The widespread car ownership in the Netherlands' (Zijlstra et al., 2022).

- Prof. Emer. dr. Hans Jeekel is emeritus professor Societal Aspects of Mobility at Eindhoven University of Technology. He has experience in several government organisations and obtained his PhD with a dissertation titled 'The car-dependent society.'
- Prof. dr. ir. Dick Ettema is professor of Urban Accessibility and Social Inclusion in the Department of Human Geography and Spatial Planning in Utrecht University. His research focuses amongst other things on mobility innovations, travel behaviour and inclusion.

Car dependency in general is considered to be caused by remote destinations and diverse activity patterns of people – in multitude and location of activities (Ettema); a lack of investments in alternative transport modes such as public transport (Ettema; Jeekel); and the feeling of freedom a private car can provide (Ettema). Two of these causes seem to be objective and one subjective. However, Ettema notes that sometimes the feeling of freedom is not merely subjective: a lack of alternatives to the car results in the car objectively providing more freedom to the owner. Similarly, alternative transport modes can objectively be available, but the potential users might never manage to explore them and therefore do not consider them proper alternatives (Jeekel): "The car is generally assumed to always be faster than public transport, even though this is not always true, especially in urban areas and between different city centres." All three interviewees mention the fact that car dependency consists of both objective and subjective aspects and that these are closely related. Additionally, Zijlstra adds the influence of personal, environmental, and situational contexts that make it difficult to objectively determine car dependency. Examples of these contexts are personal disabilities or anxiety of traveling at night, weather events, and (un)planned maintenance influencing travel time reliability.

Relating this to the literature findings, the interviewees disagree with several operationalization trends identified by Muñoz et al. (2024) since they do not contain subjective factors. Zijlstra for example mentions that the often-used approach of operationalizing car dependency as an accessibility outcome remains difficult since many aspects of this remain subjective (e.g. the definition of which amenities or job(types) should be accessible). The interviewees seem to confirm the need to operationalize car dependency as an interaction of objective and subjective factors.

All three interviewees see car dependency as a problem. Even people who do not own a car can be car-dependent due to a lack of suitable transport modes (Jeekel) – e.g. people with mobility impairments. This group could go unnoticed in the fourth operationalization approach identified by Muñoz et al. (2024) (see section 2.1). Jeekel adds that the problem with car dependency occurs mainly with medium-distance trips: the distance is too large for the bike, and the available public transport (buses or sprinter trains) is unreliable and uncomfortable. Ettema seems to agree as he mentions that efforts to reduce car dependency have only been somewhat successful in urban areas where travel distances are short and there are many alternative transport modes. Urban areas also often disincentivise car usage (e.g. by high parking costs and low speeds for cars) (Ettema). Both Jeekel and Ettema mention car-restricting policies to be essential for reducing car dependency and car use, in addition to upgrading and incentivising alternative transport modes. Ettema does state however, that car-restricting policies are difficult to implement in Dutch policymaking, where public support is important, and these policies are often unpopular. He calls for the right narratives to increase public support and enable systemic change.

On the impact of the presence of automated vehicles (AVs) on car dependency, Zijlstra was quite clear. He argued that getting individuals a car or an AV can solve that individual's accessibility issues, but not their car dependency. Underlying issues regarding the lack of nearby amenities or traffic safety issues due to the presence of cars will remain[2]. Only when an AV system is collective, open for all, and affordable can it serve more as a bus service instead of a car. Then it could contribute to reducing car dependency and thus improve inclusion in transportation (Zijlstra). Ettema poses the question whether AV systems should be implemented as commercial service or public good. This relates to the coverage of shared AV systems. The concern is that commercial deployment of [shared] AVs often results in implementation in urban areas where accessibility is already high, while these systems could actually help solve accessibility issues in rural areas as well (Ettema; Zijlstra). In addition to the aforementioned issues associated with the region of AV deployment, distribution of the effects among different population groups (e.g. certain groups experiencing all positive effects while other groups experience all the negative effects) are also important to consider (Ettema). This is important especially when public money is used for subsidies or required infrastructure investments – e.g. charging infrastructure or additional parking spots for idle AVs (Ettema).

2.3 Definitions and Assumptions

Based on the literature review and the expert interviews on car dependency and automated driving, some definitions were selected to be used in this report. They are shown in table 1 below.

Table 1. Selected definitions and assumptions of car dependency and automated driving.

Car dependency	Car dependency is a concept that describes to what extent someone depends on the car as a mode of transport. It consists of an objective component and a subjective component.
Objective car dependency	Objective car dependency is the component of car dependency that is influenced by objective factors such as the availability and the costs of alternative transport options, or the distance to essential amenities.
Subjective car dependency	Subjective car dependency is the component of car dependency that is influenced by more subjective (and often personal) factors such as one's mobility habits, the empowerment one experiences by owning a car, and one's car-related identity.
Automated driving	This report assumes a future state in which automated driving is common practice on the Dutch roads. Automated vehicles (AVs) of SAE-levels 4 and 5[3], which can be used without involvement of a human driver (within a certain condition for level 4 vehicles), are widely available and in use. A more technical description of these vehicles is given in section 3.1.

[2] Automated vehicles are expected to be safer (more sensors, shorter response times, etc.) than human-driven vehicles. However, AVs might also become heavier, resulting in larger stopping distances. Also, (experienced) traffic safety issues regarding the presence of traffic – such as ease of crossing a road – might remain.
[3] SAE driving automation levels 4 and 5 refer to vehicles with driver assistance system that can drive the vehicle autonomously under respectively limited (level 4) or all (level 5) conditions (SAE International, 2021).

2.4 Causal Loop Diagram Car Dependency

Based on the literature review conducted, expert interviews performed, and workshops and meetings held among the TrafficQuest team, several factors connected to subjective or objective car dependency were identified. These factors were used to develop a causal loop diagram (CLD) of car dependency, which is presented in Figure 2. The list of all factors contained in the CLD presented in Figure 2 as well as the source (proposed by authors or based on the consulted literature) are available in Appendix 1.

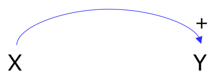
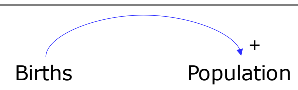
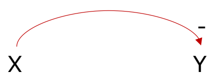
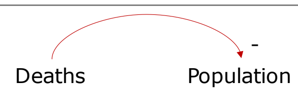
Causal loop diagrams can be helpful tools for the exploration of complex systems, as they serve as a visual representation of hypothesised elements of a system and how they relate to each other within specific system boundaries (Beenackers et al., 2024). CLDs can therefore support the understanding of complex phenomena by allowing one to "map the complexity of a problem of interest that comprises variables, causal relationships and polarity" (McGlashan et al. 2016, p.2).
The boundaries of a system are a crucial aspect of a CLD, and their specification depends on the purpose of the discussion, as "all system diagrams are simplifications of the real world. We each choose how much complexity to look at" (Wright & Meadows, 2008, p.28). For the purposes of this report, the elements within the CLD of car dependency presented in Figure 2 were derived from scientific and grey literature on car dependency or proposed by the authors following group discussions. The factors are organised in seven clusters with different colours:

- **Mobility behaviour (tyrian purple).** Includes factors directly related to mobility or car dependency, such as "car dependency", "car ownership", "car use", or "attractiveness of public transportation".
- **Infrastructure factors (red).** Includes factors related to infrastructure aspects of cities and regions that can influence car dependency, such as "road capacity", "urban sprawl", "distance to essential activities", or "availability of public transportation stops".
- **Economics factors (orange).** Includes cost-related factors affecting transportation choices, such as "car related costs", and "cost of public transportation".
- **Sociodemographic factors (lilac).** Includes sociodemographic factors relevant for factors such as car ownership and use, including "household size", "availability of disposable income", or "possession of driving license".
- **Personal factors (yellow).** Includes subjective and personal factors of individuals that can play an important role in their mobility choices and habit, including "car-oriented identity", "car related empowerment", "feeling of insecurity in public transport", "presence of (physical) disabilities", or "perception of car ownership as a choice".
- **Social norms factors (light cyan).** Includes aspects that affect the societal perspective on car related mobility, public transportation, and others. This cluster includes what some authors mention as "societal habits" and the "culture of car use". Factors such as "Car-oriented mindset and preferences", "Attractiveness/Willingness to use car for transportation", "Perception of car as only suitable transport mode", or "Marginalisation of alternative modes of transport" are examples of factors within this cluster.

- **Environmental factors (green).** Includes factors related to the interaction between the usage of car for mobility purposes and the environment, including "car related emissions", and "climate change effects".
- **Benefits and policies (blue).** Includes governmental policies or company benefits that affect the mobility choice of individuals, being that towards more or less car use. Factors such as "Travel allowance benefits", "Public transportation policies", or "Company car benefits" are examples of factors within this cluster.

Beyond the factors themselves, as mentioned by McGlashan et al. (2016) , a CLD consists of also the connection between these variables, and the polarity of these connections (positive or negative). Factors are connected via causal links (arrows), and these connections can have either a positive (+) or negative (-) polarity, indicating how a dependent variable changes as a result of changes to the independent variable. Table provides examples of causal relationships and polarities.

Table 2. Explanation and examples of positive and negative polarities

Causal relationship	Explanation	Example
	**Positive (+)**: variable Y moves in the same direction as variable X (all else equal). This means that an increase in variable X causes an increase in variable Y, and a decrease in variable X causes a decrease in variable X.	
	**Negative (-):** variable Y moves in the opposite direction as variable X (all else equal). This means that an increase in variable X causes a decrease in variable Y, and a decrease in variable X causes an increase in variable Y.	

In a CLD, the link polarity (positive or negative) only indicates the direction of change, not the size of the change – the indication of the effect is only qualitative. In addition, the causal relationship between factors does not have to be a linear relationship. The interconnection of multiple elements in a system can result in (multiple) feedback loops, which a CLD can help identify and make explicit. A **feedback loop** is formed when a series of variables and causal links produce a closed ring of causal influences, leading to the result of a causal impact to return to influence the original cause of that effect (Ford, 2019). Feedback loops can be either reinforcing or balancing. In a **balancing feedback loop**, the resulting effect of the causal links over time restricts the movement of variables (Ford, 2019), meaning that a balancing feedback loop opposes whatever direction of change is imposed on the system (Wright & Meadows, 2008). In a **reinforcing feedback loop**, the cumulative effect of the causal links amplify an initial change, potentially leading to a virtuous circle of healthy growth or a vicious circle of runaway destruction (Wright & Meadows, 2008).

The analysis of feedback loops in complex issues such as car dependency is highly important in order to identify the dynamic mechanisms through which car dependency can (potentially) increase or decrease over time. As stated by Pokharel et al. (2023), car dependency becomes inevitable when all reinforcing feedback loops run in a continuous process. By identifying the feedback loops affecting car dependency, one can also see opportunities for interventions that can shift the loop dominance in the system.

In this study, by focusing on the variable "**car dependency**" in the CLD depicted in Figure 2, 21 feedback loops were identified (5 reinforcing, 16 balancing). Appendix 2 presents the visual representation, loop polarity (reinforcing or balancing) and the description of how each loop operates within the system depicted in Figure 2. It is important to emphasize that these feedback loops only provide a visual representation of the various pathways through which car dependency can be reinforced or balanced and are not sufficient to assess the overall pattern depicted by the system over time. For a complete analysis of the behaviour of the system over time, computer simulations of the complete system are generally required. This will then help to reveal which loops (reinforcing or balancing) will dominate the system over time (Sterman, 2000).

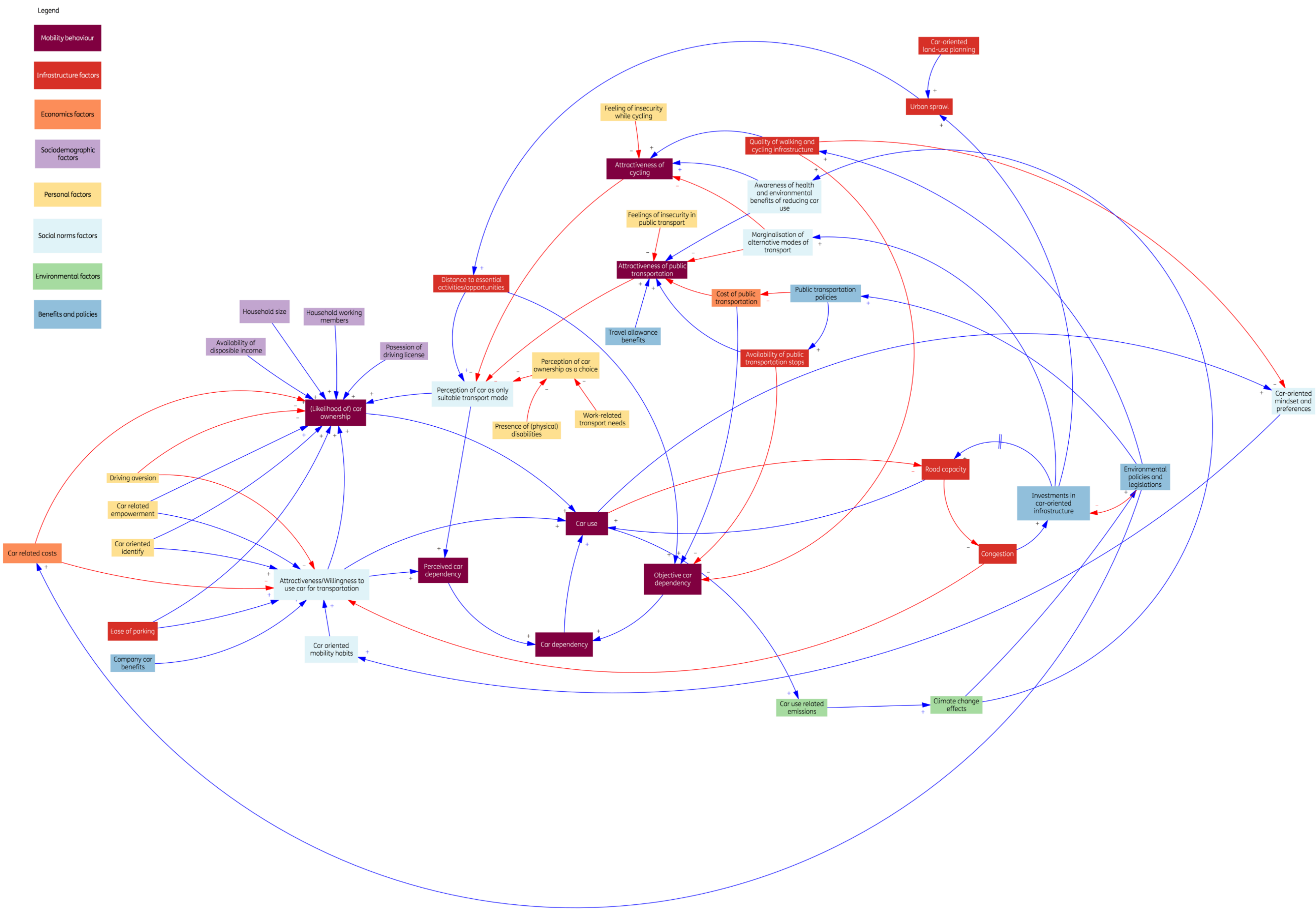


Figure 2. Causal loop diagram (CLD) of car dependency

2.5 Expected Impact of Automated Driving on Car Dependency

Automated vehicles are expected to strongly influence urban mobility and transportation choice of individuals. Some of the expected potential benefits include increasing mobility and accessibility for those unable to drive or use public transport, reducing travel time and traffic jams, reducing traffic related emissions (assuming fully electric AVs), and reducing traffic accidents caused by human error. On the other hand, automated vehicles also bring with them potential drawbacks, such as a possible increase in car travel, potential competition with other forms of transportation (e.g., trams, buses, metro, cycling), and increased urban sprawl as people are encouraged to move further way. Both positive and negative (potential) effects of AVs in the mobility system are still projections, since at the moment autonomous vehicles have not been widely deployed.

In this study, the goal is to explore what the impact of AVs on car dependency could be. For this purpose, three different potential future scenarios are explored: **(1)** private AVs, **(2)** shared AVs (e.g., robo-taxis), and **(3)** shared AVs with shared rides (e.g., robo-buses or automated shuttles). In the first scenario, the majority of the AV uptake will take place as private vehicles. In the second scenario, the major AV adoption takes place in the form of on-demand shared vehicles (automated taxis or robo-taxis). In the last scenario, AVs are mainly adopted as collective transportation. This means the vehicles are shared and also the rides are shared by multiple people (e.g. automated buses). In reality, the future might be a combination of these three scenarios. However, for the purpose of exploring the different impact of these different types of AVs, we consider these scenarios separately.

As these are explorative future scenarios, they are subject to several assumptions. First of all, it is assumed that the AVs that are present in all scenarios are mature and function as designed. This means that the introduction period in which initial (technological) issues of AVs, which limit the functionality and cause all kinds of negative effects, are not considered. Furthermore, legislative challenges are also not considered and the AVs in the scenarios are assumed to be fully legalised to be used as designed (SAE-levels 4 and 5). The main scenario-specific assumptions can be found in Table 3.

Table 3. Explorative scenarios and their underlying assumptions.

Scenario	Majority of AV uptake in form of:	Main assumptions
Private AVs	Private AVs	• Regular private vehicles are still available • Uptake of private AVs depends on retail price of AVs
Car-sharing (Shared AVs, private rides)	Robo-taxis	• Private vehicles are still available • Free-floating shared AV system • Availability is high and costs are low
Ride-sharing (Shared AVs, shared rides)	Automated buses or shuttles	• Private vehicles are still available • Rides are shared with other people, no private vehicle • Free-floating shared AV system • Availability is high and costs are low

The CLD presented in Figure 2 is used to identify which factors are expected to be affected by the introduction of AVs in the three scenarios. The factors expected to change (within the scope of the CLD depicted in Figure 2) are presented per scenario in the following tables. These tables also contain some additional assumptions for the scenario when this was deemed to be required to substantiate certain expected effects. These tables are used as input for chapter 4, which contains the detailed analysis of the systematic impact of the different scenarios on car dependency, car ownership and car use is determined. Furthermore, the scenario analysis discusses the expected impact of these scenarios on traffic management and the role traffic management can play in each scenario (based on the findings of chapter **Fout! Verwijzingsbron niet gevonden.**).

Table 4. List of factors expected to be affected by private AV scenario.

Affected factor (from CLD in Figure 2)	Direction of change	Rationale behind impact of private AV scenario
(Likelihood of) car ownership	(↑) (slight) increase	• Based on the assumption that the current fleet/expected fleet growth would be replaced by AVs, then no significant increase in car ownership would be expected. • If the perceived convenience of using an AV increases significantly, then car ownership can also potentially increase. On the other hand, if the price of an AV is much more expensive than a non-AV, uptake can also be reduced.
Attractiveness/ Willingness to use car for transportation	(↑) Increase	• The attractiveness of using a car (AV) for transportation is expected to increase with the introduction of private AVs, especially if people "…succumb to the allure of convenience and switch from public transport, or make more journeys" (Kleinman & Rohr, 2018). Ease of parking also influences the attractiveness of using a car for transportation.
Ease of parking	(↑) Increase	• With privately owned AVs, individuals would not need to park the car themselves any longer, which would increase the convenience for them. However, at some point parking spaces would still be necessary, either for when the AV is to be parked at home or a parking spot somewhere around the workplace. Therefore, even though private AVs can lead to an increase in the ease of parking, shared AVs are expected to more strongly affect this factor.
Congestion	(↑) Increase	• Based on the assumption that the current fleet/future fleet will migrate to private AVs, traffic volumes are not expected to go down. Traffic volumes can even go up, considering that people might choose to use the car (AV) more often and for purposes that they wouldn't before and that there will be empty AVs travelling around, which can increase congestion.
Urban Sprawl	(↑) Increase	• As autonomous vehicles facilitate transport (e.g., people can take productive or relaxing activities while in transit), the Value of Travel Time (VoTT) can be expected to decrease (i.e., cost associated with the time spent traveling), making people more willing to live further away and engage in longer (but more comfortable) trips.

Table 5. List of factors expected to be affected by the shared AVs (robo-taxis) scenario.

Affected factor (from CLD in Figure 2)	Direction of change	Rationale behind impact of the shared AVs (robo-taxis) scenario
(Likelihood of) car ownership	(↓) Decrease	• The availability of shared AVs (robo-taxis) can have the potential to reduce car ownership, especially if the price to (regularly) use a shared AV is lower (e.g., via market competition, wide scale deployment etc) than the total cost of ownership (TCO)[4] of a private car (Shared autonomous vehicles (SAVs) "have the power to gradually replace private car ownership in numerous cities within the next decades" (PwC, 2024))
Attractiveness/ Willingness to use car for transportation	(↑) Increase	• The attractiveness of using a car (AV) for transportation is expected to increase with the introduction of shared AVs (robo-taxis), as people can more easily request on demand transportation. Ease of parking and car related costs also influence the attractiveness of using a car for transportation.
Ease of parking	(↑) Increase	• Shared AVs (robo-taxis) are expected to improve the ease of parking even more than private AVs, as with shared AVs individuals do not have to worry about parking a vehicle at all, either at work (or other activities) or at home.
Congestion	(↑) Increase	• Traffic volumes can go up, considering that people might choose to use the car (robo-taxi AV) more often and for purposes that they wouldn't before. • Additionally, it is expected that there will be empty AVs (robo-taxis) travelling around, which can increase congestion.
Congestion	(↓) Decrease	• Although shared AVs (robo-taxis) can increase congestion, they can also reduce congestion via other means. As people start using robo-taxis, there theoretically is a potential reduction in traffic volume due to increased car occupancy (number of shared trips). (International Association of Public Transport, 2017) Although this effect might be limited.
Urban Sprawl	(↑) Increase	• As autonomous vehicles take over the driving task (e.g., people can take productive or relaxing activities while in transit), the Value of Travel Time (VoTT) can be expected to decrease (i.e., cost associated with the time spent traveling), making people more willing to live further away and engage in longer (but more comfortable) trips.
Car related costs	(↓) Decrease	• If shared AVs are deployed in a large enough scale and in a competitive market, prices for (regular) shared AV rides can become more interesting from a financial standpoint than having your private car. ("Matched against the total cost of ownership of private cars today, shared AVs would also be much cheaper, lowering the cost per passenger kilometre by as much as 30%." (Lang et al., 2020))
Attractiveness of public transportation /cycling	(↓) Decrease	• Shared AVs, in this scenario, are not considered conventional public transport, but commercial taxis. They can therefore compete with public transportation services and can cause passengers who typically used PT/cycling or other transport modes (e.g., due to not owning a private car) to switch to shared AVs.

[4] Total cost of ownership (TCO) refers to the overall expense of buying and maintaining a product over its entire life. This includes the initial purchase price as well as operational costs throughout its use. For a private car, TCO encompasses elements such as car payments, registration fees, insurance, maintenance, fuel, parking fees, and depreciation.

		This is especially important if factors like convenience, availability, and price related to shared AVs favour such a shift. It is important to emphasise that this effect of the attractiveness of public transportation/cycling might not be a direct effect of the introduction of shared AVs, but rather a consequence (on a systemic level) from such an introduction.

Table 6. List of factors expected to be affected by the shared AVs (robo-buses) scenario.

Affected factor (from CLD in Figure 2)	Direction of change	Rationale behind impact of the shared AVs (robo-buses) scenario
(Likelihood of) car ownership	(↓) Decrease	• The availability of shared AVs in the type of larger occupancy robo-buses can have an impact of reducing car ownership. However, it is expected that this would have a lower impact than shared-taxis (see scenario analysis in chapter 4), as robo-buses might not be as readily available as a robo-taxi (or a private AV), rides would likely follow to some extent pre-defined routes that passengers need to accommodate to (as in regular buses or trams), and robo-buses rides would be (potentially) shared with multiple other passengers. Therefore, it could be the case that less people are willing to not have a private (autonomous) vehicle and use robo-buses than robo-taxis.
Ease of parking	(↑) Increase	• Shared robo-buses are expected to provide the biggest improvement in the ease of parking, as they can be expected to ride for long periods of time and take up less space, since they only need to park at night or special cases (like regular buses). Individuals do not have to worry about parking a robo-bus.
Congestion	(↓) Decrease	• Robo-buses can reduce congestion given the fact that they have a far higher vehicle occupancy (e.g., 15-20 passengers) than both private AVs and robo-taxis.
Urban Sprawl	(↑) (slight) increase	• Robo-buses can lead to higher urban sprawl, but this is expected to be lower than both private AVs and robo-taxis. Robo-buses in more sparse regions can be expected to run less frequently (as there might be less demand), potentially increasing the costs of the robo-bus rides. Additionally, individuals might still need to take a robo-bus to the nearest train/metro station in order to reach where they want to go, as they might not be able to dictate the journey of the robo-bus (as it is expected for robo-taxis and private AVs).
Cost of public transportation	(↓) Decrease	• The costs for individuals can be expected to go down if robo-buses are incorporated into the mobility system as another form of public transportation. However, it is also expected that public authorities will incur costs to ensure that robo-buses serve low-demand areas in an equitable way.
Attractiveness of public transportation /cycling	(↑) Increase	• The attractiveness of using a robo-bus for transportation can potentially increase, especially if people have some autonomy to request a robo-bus (instead of having to wait fixed time schedules), if costs are low and availability is high. However, the presence of other people riding the robo-bus might also affect the convenience/productivity of individuals, making robo-buses less attractive than robo-taxis.

3 Traffic Management and Automated Driving

The second step in this research is the exploration of the impact of the widespread uptake of AVs on traffic management (TM). We start with a scan of literature that first defines what traffic management is and how automated vehicles influence the flow of traffic, in general, on highways and in urban areas. Afterwards, these insights are deepened and contextualized with an expert interview. In chapter 4, the insights of this chapter are combined with the insights in the potential effects of different AV scenarios on car use and car dependency.

3.1 Literature review

Earlier TrafficQuest reports defined traffic management as actions that aim to influence traffic supply and demand in such a way that traffic demands and the capacity supply of the network are better matched, both in time and space (Hoogendoorn et al., 2011). They define that the problems encountered on the road network mainly concern specific bottlenecks and moments (i.e. peak hours, incidents, and events). By spreading traffic demand or dynamically adapting the supply of infrastructure, the existing road network can be better utilised. Typical, conventional TM measures include ramp metering, dynamic speed limits, peak hour lanes, but also traffic information communicated through panels above the road or other channels. The measures are primarily intended to improve accessibility, but they are also increasingly being used to improve road safety (e.g. through queue tail warning) or quality of life (e.g. by using speed limits) (Hoogendoorn et al., 2011).

In conventional traffic, TM can already fulfil various traffic-related functions:

- **Monitoring and detecting**: the monitoring and detecting of traffic and incidents.
- **Informing**: signposting, route information, network status, travel times, lane allocation.
- **Advising**: advising on lanes, speeds, and alternative routes.
- **Warning**: queue tail warning, queue tail signalling, dangerous situations, disturbances.
- **Management and control**: reducing speed limits, changing lane allocations, opening or closing lanes, processing height alerts, stopping traffic, overtaking prohibition, ramp metering, buffering.

The capabilities and roles of TM can change with widespread adoption of automated vehicles (AVs). As mentioned in section 2.3, a widespread adoption of AVs is considered to be a future situation where AVs of SAE-levels 4 and 5 are commonly available and in use. These AVs per definition contain a sensing system with a variety of sensors gathering real-time data of the surrounding environment to ensure safe automated driving. Efficient automated driving, however, would only be possible when AVs communicate with other (automated) vehicles, infrastructure, personal devices of cyclists and pedestrians, and the cloud (Martínez-Díaz & Soriguera, 2018). This aspect differentiates these cooperative, connected, and automated vehicles from autonomous vehicles, which only have the sensing system and not necessarily the communication (Wilmink et al., 2014). This added connectivity of automated vehicles increases the opportunities for, and the prominent role of TM.

Impact of connectivity of AVs on TM

The large-scale presence of connected AVs in a transport system can significantly improve the real-time availability of data on the current state of the transport system. This data, which is communicated to traffic TM systems through vehicle-to-infrastructure (V2I) communication, can help to more quickly identify congestion and incidents and adapt TM strategies to mitigate the impact on the transport system (Musa et al., 2023). This impacts the TM capabilities in *monitoring and detecting* roles and therefore allows for more adequate action in *informing, advising, warning* and *management and control* roles. The *informing, advising,* and *warning* roles themselves are also influenced by connected AVs. Infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communication allows for direct in-car messages, adding new options to the conventional communication methods available to traffic managers. The receiver of this communication, however, will in many cases be the automated driving system of the vehicle, and not the human driver. This impacts the format in which messages are communicated, but also the frequency in which communication to the vehicle can and should take place – assuming the automated driving system can handle significantly more consecutive and simultaneous inputs than a human driver, but also needs a constant access to traffic management data to complement its own sensor data to plan its trajectory (TM2.0 Taskforce 6, 2016). The TM controller can also receive confirmation from the AVs that they have received the information or instructions (Portouli et al., 2017).

Besides digital communication, some conventional TM communication methods (e.g. hand signs by traffic managers) should be interpretable by AVs as well (TM2.0 Taskforce 6, 2016; Portouli et al., 2017). This is especially relevant in the transition period when both AVs and human-driven vehicles (HDVs) are present on the road and conventional communication methods might still often be used. Near the end of this transition period, when the share of HDVs is low, important TM communication still needs to be available to HDVs. Therefore, either conventional TM communication should remain available or these last HDVs need to be adjusted to be able to receive the AV-focused TM communication.

Impact of automated driving on TM

Literature on the impact of automated vehicles on TM can roughly be divided into three categories: general impact on traffic system; impact on highways (e.g. platooning strategies); and impact in urban areas (e.g. intersection control strategies or parking regulation). Special attention is paid in literature to the transition period when traffic consists of a mix of AVs and HDVs – a period which is assumed to be finished in the scenarios of chapter 4 but is still important to consider.

General impact of automated driving on system-wide traffic management

AVs will give traffic management more direct control over the traffic than HDVs. In case of warnings or instructions from the traffic manager, each human driver might interpret them differently and might not always adhere to them – which makes human drivers more difficult to influence. AVs will be more directly influenceable by traffic management instructions when they are programmed to adhere to the instructions. Also, with AVs, the traffic controller can get a direct confirmation that the AV is following the instructions. This increased level of control does not only apply in full-AV traffic. In mixed traffic conditions, traffic managers could adjust the speed of connected AVs to indirectly influence the speed of following (human-driven) vehicles and in this way manage the combined traffic flow (Wu et al., 2024). In traffic jams, this could help dilute the shockwave of traffic (Portouli et al., 2017), or buffer the traffic entering the congested road. When people become more trusting of AVs, they might allow the AV to control more aspects of their trip – e.g. route choice and departure time (Wu et al., 2024). This would allow for more elaborate options of traffic management: demand spread and system-optimal routing. Both TM strategies aim to use the control over AVs' routes and departure times to minimize system travel costs instead of the minimization of (individual) user travel costs that human drivers do (K. Zhang & Nie, 2017; as cited in Wu et al., 2024). By combining these AV control strategies with pricing mechanisms, efficient and low-emission traffic can be pursued (F. Zhang et al., 2022; as cited in Wu et al., 2024). Minimum ratios of connected AVs that are required to significantly impact traffic depend on the road network. For the majority of networks, this minimum AV ratio does not exceed 23% - meaning that on most networks, 23% AV adoption would already significantly impact traffic. These ratios can often be reduced by combining AV control with pricing policies for all vehicles (Chen et al., 2019).

Impact of AVs on TM on highways

AV platooning can create groups of AVs that travel safely with small spaces in between (smaller than human driven vehicles) (Martínez-Díaz & Soriguera, 2018). Reducing this following distance in platoons can increase the capacity of traffic flow on a road. However, this only applies to platoons of AVs. In interaction with unconnected HDVs, AVs adopt a more conservative driving style and thus show a bigger following distance than human drivers. In a mixed traffic situation with limited adoption of AVs, traffic flow capacity can actually decrease if AV platoon forming is not stimulated (Ren et al., 2024). Therefore, platoon control will become an important new role for TM – one that can be added to either the *advising* or the *management and control* function in the list above.

J. Yang et al. (2024) address the issue of capacity reduction in mixed traffic (AV and HDV) by proposing different strategies for operating separate lanes for AVs (optionally in combination with existing High-Occupancy Vehicle lanes). Similar strategies for dedicated AV-lanes (Wang et al., 2024) or multi-function lanes for buses and AVs (Zhang et al., 2024) in mixed traffic situations have been simulated with positive results for urban environments as well. These dedicated lanes could even prove useful in stimulating the AV adoption rate (Pourgholamali et al., 2023). If these dedicated AV-lanes are separated from lanes with HDV traffic, they could even be dynamically used in both directions – depending on the direction of the peak period. This does, however, require significant safety precautions in mixed traffic (AV/HDV) conditions. TM will become increasingly important for managing (access to) these dedicated AV-lanes, both on highways and in urban areas.

Impact of AVs on TM in urban areas

In urban areas, AVs can have an impact on the management of signalized intersection. Their connectivity means that data such as their position, speed and planned route can be communicated with the TM system. This data can be used to optimize the traffic signal cycle (Musa et al., 2023) and sharing data on the traffic signal cycle can allow AVs to optimize their route and speed (Ying & Feng, 2023). These developments will also allow for more integral management of neighbouring intersections and the system as a whole, as mentioned in the system-wide impacts above. Even with lower adoption rates of AVs and only basic I2V and V2V communication, Z. Yang et al. (2024) demonstrate the potential of AVs with a connection to traffic signal controllers driving more efficiently than human drivers. With almost exclusively SAE-level 5 AVs on the road, even the traffic signal cycle could change as there might not be a need for the yellow light anymore – the timing of the red light can be digitally communicated to the vehicle.

The presence of AVs will have an impact on parking in urban areas. AVs, as opposed to HDVs, no longer have to be parked in close proximity to the destination. The passenger can be dropped at the trip's destination, after which the AVs can drive itself to a parking spot elsewhere. This can be a parking spot with lower parking costs than generally seen at the trip destination. This phenomenon can have a number of effects:

- Parking related costs for the owner/user (e.g. direct parking costs, cost of time used to search a parking spot, cost of distance to be covered between parking and destination) will decrease. This mainly applies to private AVs. For shared AVs, the assumption can be made that these are most often in-use during the day and parking costs at night are shared among the many users over the day. This decrease of costs for users might lead to an increase in demand for (shared) AVs (Calvert et al., 2021).
- The number of parking spots in city centres and other high-density areas can (in case of high adoption rates of AVs) be reduced. This frees up space that can be redesigned for other uses. Dynamic use of these parking spaces could also be possible – think drop-off and pick up location during peak hours and terrace at night. For AV traffic, the access to these locations can then be managed digitally: another role for TM.
- An increase in empty kilometres driven by AVs will occur. In case of private AVs, this mainly concerns traffic to and from parking locations. For shared AVs, this can be trips between different passengers, but also cruising around while waiting for a next trip. Both increase traffic intensity in high-demand areas. Traffic and parking management policies might be needed to limit these empty kilometres.

Van den Hurk et al. (2020) suggest AV-parking policies that favour local parking for short durations and remote parking for longer durations to limit the number of empty kilometres driven. Meanwhile, in a mixed traffic situation, they suggest prohibiting AV street-parking in city centres to keep these spots available for HDVs of which the drivers still need to walk the distance between parking spot and destination. Lastly, they call for TM policies (e.g. dynamic pricing) to manage pick-up and drop-off of passengers by AVs, especially in high-demand areas.

Take-aways of literature on AVs and TM

The impact of AVs on the role of TM can be categorized in three main trends: new opportunities for communication, new opportunities for TM control interventions, new requirements for TM policies. In the table below, these main trends are summarized.

Table 7. Main trends of the impact of AVs on traffic management

Trend	Main impact	Considerations
New data and communication opportunities and responsibilities	• New opportunities to gather data on traffic states through V2I communication. Enables proactive TM based on planned trajectories. • New opportunities and responsibilities to share relevant data and information with AVs through I2V/V2V communication. • Connected AVs can give direct confirmation when it changed its trajectory based on the TM communication.	• In mixed traffic conditions, conventional TM communication should still be used for HDVs. • AVs should be able to interpret conventional TM communication. • With AVs instead of HDVs, TM communication might serve a different purpose: less informing or advising, more controlling – although the human passenger might still want to be informed.
New TM control opportunities	• AVs allow for more direct influence on traffic than HDVs and therefore allow for new TM control opportunities. • Controlling AVs directly can allow for system optimization. • New opportunities: AV platoons on highways or traffic signal optimization combined with AV trajectory optimization.	• This assumes AVs are programmed to always adhere to TM instructions they get. • The effect of these TM instructions can be limited in mixed traffic (AV & HDV) conditions or when AVs do not strictly adhere to TM instructions.
New TM policy requirements	• TM policies are required to mitigate some (potential) negative effects of AVs. • Examples: increased vehicle kms through empty trips of AVs; busy pick-up/drop-off locations in cities; or busy idle-AV parking spots outside the city centre.	• In the early days of SAE-level 4 and 5 AVs, these mitigating policies might not yet be in place. • Both AV manufacturers and shared AV operators should be involved in shaping these policies.

3.2 Expert Interview on TM in the era of automated driving

An expert interview on the impact of AVs on the role and possibilities of TM was conducted with Boris van Waterschoot, senior advisor on Human Factors and Automated Driving at Rijkswaterstaat (RWS), the executive agency of the Dutch Ministry of Infrastructure and Water Management (IenW). The interview touched upon three main topics: opportunities for TM in the era of AVs, risks and considerations around AVs, and requirements for successful implementation of AVs.

Opportunities for TM in the era of AVs

Current TM policies aim to influence human drivers in their driving task, which proves to be difficult. AVs will allow to have more direct control over the fleet of vehicles on the road. If the system works as designed, TM could direct traffic almost exactly as desired. This could have a large impact on throughput of the transport system (Van Waterschoot). A strong assumption is, of course, that AVs will adhere to TM instructions they receive. Ensuring this will require strong coordination between government or road operators and AV manufacturers – as is discussed in the section on requirements for successful implementation of AVs below.

Risks and considerations around AVs

The connectivity that AVs add, and the opportunity for TM to use more digital communication (V2V, I2V, V2I) also pose a risk. When the whole traffic management system relies on this extensive communication, it can make the system vulnerable to all kinds of threats (e.g. system errors, power outages, or cyber-attacks). AVs will require redundant safety systems to overcome minor system component failures. AVs with many redundant systems, however, are also costly. Especially in the scenario with private AVs, these costs can be an issue. Therefore, attention should be paid to these AVs that system redundancy installed for safety is not removed to cut costs (Van Waterschoot). These concerns were also shared by the nineth taskforce of the TM2.0 platform (Portouli et al., 2017).

Even with redundant safety systems, AVs can still pose safety risks. For the future scenarios in this research, the assumption is made that the technology works as designed and does provide similar safety levels as human drivers - and in some situations even higher levels. In reality however, a transition period towards this presence of safe AVs will take place, in which AVs might experience flaws and safety might not always be guaranteed. Common human flaws while driving (e.g. lack of attention, tiredness, overconfidence) will likely occur less with AVs. However, AVs can experience different types of flaws that human drivers experience less, such as having trouble identifying objects and interpreting their potential consequences (e.g. a football rolling on the street might indicate playing children being around) (Van Waterschoot). These interactions and the ability to anticipate can be hard to automate. Testing AVs in real life situations might help improve the technology and reduce such unsafe situations. Paradoxically, this then requires allowing AVs that have not yet proven their full safety potential to be tested on the road to increase safety of AVs .

Requirements for successful implementation of AVs

The TM opportunities that the connectivity of AVs and the direct control over the AV fleet bring, can only grow to their full potential when there is some sort of TM plan (TMP) behind it: an ideal traffic situation, TM scenarios to get there, and data standards for V2V/I2V/V2I communication. This TMP could set the boundary conditions and requirements for the way of working of connected AVs (Van Waterschoot). When such a plan is not made and used, AVs will remain to a large extent autonomous vehicles: they plan and optimize their own journey but do not necessarily communicate with infrastructure and do not receive and follow instructions from traffic management control (Van Waterschoot). As also mentioned in the literature review above, existing autonomous vehicles that have been developed without an overarching plan in place, do not have extensive V2V/I2V/V2I communication and can actually reduce the capacity of a road due to large following distances.

A TMP for the AV era will require AV manufacturers, road authorities, government bodies, service providers, and other involved parties to be on the same page and commit to this plan and to the various requirements and boundary conditions that follow from it. On the basis of such a plan, agreements can be made for example on standard information that AVs should communicate to TM control, standard information that should be communicated to AVs, standard types of TM instructions that can be given to AVs in certain situations, and the expected response of AVs to these instructions. The governance challenge of coordinating this and getting the commitment of all involved parties might be more complex than the technical developments that are needed (Van Waterschoot). During earlier developments such as the introduction of ADAS systems and in-car communications, all manufacturers developed their own systems without much coordination or attention to inter-compatibility of these systems. The question is if initiatives of coordination on these developments may be expected from the private sector. The role of coordinator for such developments and initiator of a TMP for the AV era might be more fitting for a governmental party – likely with cooperation on international level. These remarks by Van Waterschoot are confirmed by the TM2.0 platform, which also stretches the importance of agreements between all parties on i.e. data standardization and cooperation frameworks for AVs (TM2.0 Taskforce 14, 2017).

4 Scenarios of automated driving and their impact on car dependency and traffic management

In order to explore the future impact of AVs on car dependency and traffic management in the Netherlands, an explorative scenario analysis was performed. The three different future scenarios regarding the uptake of AVs were presented in section 2.5: **(1)** private AVs, **(2)** shared AVs (e.g., robo-taxis), and **(3)** shared AVs with shared rides (e.g., robo-buses or automated shuttles). In each of the following sections, one scenario is evaluated. Each scenario was evaluated using the following steps:

1. Identification of the loops in the CLD that contain both a factor that is expected to be directly impacted by a scenario (as described in section 2.5), and one of the three factors of interest: car dependency, car ownership, or car use.
2. Based on these loops, the possible paths from the expected direct impacts of the scenario to the factors of interest were analysed to determine the effect (increase or decrease) (e.g. a decrease in congestion can lead, through an increase in the attractiveness of the car, to an increase in car use). Each path has a code[5] which can be used to find the full path description in appendix 3.
3. The insights on car dependency, car ownership and car use provided by the CLD analysis are then used to determine the impact on traffic management. For each scenario, we reflect on the potential need for (new) traffic management policies.

This scenario analysis is a quick-scan analysis of the systematic effects of automated driving on car dependency and traffic management. The steps described above therefore result for every scenario in a number of paths potentially increasing a factor of interest and a number of paths potentially decreasing the factor of interest. Simulating the relations in the CLD to get to a quantification of the effects of the different paths is outside the scope of this research and would be a relevant next step (see future outlook in section 5.4).

In this scenario analysis, the multitude of paths leading to an increase or decrease of the factors of interest is assumed to give an indication of the overall direction of the expected effects and is therefore used for comparison between scenarios. This implicitly assumes that the effect of each path has an equal weight and is in the same order of magnitude. This is a simplification of reality (see limitations in section 5.3), but this does enable a first comparison of the expected systemic effects of the different future scenarios. This comparison is discussed in chapter 5.

4.1 Private Vehicle Scenario

In this scenario, the majority of AV adoption will occur as privately owned AVs. The adoption rate of AVs will depend largely on the cost of purchase of these vehicles. When this remains high (as initially expected with these high-tech vehicles), private AVs will remain for the happy few. This expectation was also shared by Zijlstra and Jeekel in their interviews. Zijlstra added the remark that a second-

[5] The paths are all coded with a scenario (S1/S2/S3), the direct impact factor at the start of the path (A/B/C/etc.), factor of interest at the end of the path (1/2/3), specific path through the CLD between start and end factors (.1/.2/.3/etc.). This results in codes such as S1A3.2.

hand market for AVs might not take off easily due to the complexity of these high-tech vehicles, which increases the difficulty for potential buyers to assess the state of the car and it's technology (this information asymmetry is described in 'The market for Lemons' by Akerlof (1978)). This can further limit the affordability for medium to lower income groups.

4.1.1 Expected impact of private AV scenario on car dependency, use, and ownership

The expected direct impacts of the private AV scenario on different factors from the CLD were described in section 2.5. Starting from these direct impacts, the feedback loops in the CLD were analysed to determine the consolidated indirect impacts of the scenario on the three factors of interest: car dependency, car ownership, and car use. Table 8 presents the overview of the consolidated impacts, after which each factor of interest is further discussed below. See Appendix 3 for details on each impact (i.e. (↑) Increase / (↓) Decrease).

Table 8. Consolidated expected effects of private AV scenario on factors of interest (see Appendix 3 for details)

Factor of interest	*Consolidated expect effect (see Appendix 3 for details)*	
Car dependency	7 paths (↑) Increase	1 path (↓) Decrease
Car ownership	5 paths (↑) Increase	1 path (↓) Decrease
Car use	14 paths (↑) Increase	3 paths (↓) Decrease

Car dependency

The CLD depicted in Figure 2 has 21 feedback loops involving the variable "**car dependency**", as depicted in Appendix 2. By focusing on the expected direct impacts of private AVs on the factors listed inTable 4, eight paths were identified out of these 21 feedback loops. Through these eight paths, this private AV scenario affects car dependency – seven of them leading to an increase in car dependency.

Four of the paths leading to an increase of car dependency start with an *increase in congestion*. Following the CLD depicted in Figure 2 shows that this might lead to *investments in car-oriented infrastructure*. This could lead to marginalisation of alternative modes of transport (i.e., cities become increasingly car-centric) and then to decreases in the *attractiveness of cycling* (S1B1.2) and *the attractiveness of public transportation* (S1B1.3). These paths then lead through an increase in the perception of the car as the only suitable transportation mode and perceived car dependency, to an increase in car dependency. However, an increase in *investments in car-oriented infrastructure* can also lead to an increase in *urban sprawl*, which increases the distance to essential activities (such as work, shopping, or leisure) and subsequently an increase in both objective (S1B1.4) and subjective car dependency (S1B1.5). Other paths leading to an increase in car dependency start from an expected increase in the *attractiveness/willingness to use a car* due to the presence of private AVs in this scenario (S1A1.1). This path increases perceived car dependency and then car dependency as well. Lastly, in this scenario, an increase in *urban sprawl* is expected. This can lead to an increase in car dependency through objective (S1C1.1) and perceived car dependency (S1C1.2).

In one of the eight paths identified via the CLD, car dependency is expected to decrease. This is the case for (S1B1.1), in which an *increase in congestion* leads to a decrease in *attractiveness/Willingness to use car for transportation*. If the attractiveness of using the car for transportation is reduced, this triggers a decrease in perceived car dependency and ultimately on car dependency (i.e., the opposite effect of path S1A1.1).

Car ownership

The CLD depicted in Figure 2 contains six paths from the expected direct effects of private AVs on the factors listed in Table 4, to an expected effect on (the likelihood of) car ownership. Through five of these six paths, the private AV scenario leads to an expected increase in car ownership, while one path is expected to decrease car ownership.

Three paths increasing car ownership are similar to paths increasing car dependency: they start with an expected *increase in congestion* and lead through increases in *investments in car-oriented infrastructure* and decreases in attractiveness of cycling (S1B2.2) and public transport (S1B2.3) or an increase in urban sprawl (S1B2.4) to an expected increase in car ownership. Also similar to car dependency, an expected increase in the *attractiveness/willingness to use the car* is expected to lead to an increase in car ownership (S1A2.1). Lastly, an increase in *urban sprawl* is also expected as a direct effect, which in turn can increase car ownership as well.

In one of the six paths identified via the CLD, car ownership is expected to decrease. This is the case for S1B2.1, in which an *increase in congestion* leads to a decrease in *attractiveness/Willingness to use car for transportation*. If the attractiveness of using the car for transportation is reduced, the opposite effect of path S1A2.1 takes place, leading to a decrease in car ownership.

Car use

The CLD depicted in Figure 2 has 45 feedback loops involving the variable "**car use**". The direct impacts of this scenario on the factors listed in Table 4 are connect to the factor car use through 17 identified paths. In 14 of the 17 paths, car use is expected to increase.

An *increase in congestion* can trigger multiple paths that reinforce car use. Most of these paths have already been discussed in relation to car dependency and car ownership. Four paths (S1C3.4, S1C3.5, S1C3.6 and S1C3.7) go via an increase in *investments in car-oriented infrastructure* and *marginalisation of other modes* to an increase in car use. Three others (S1C3.8, S1C3.9 and S1C3.10) follow the path from *increase in congestion,* through an increase in *urban sprawl* and *distance to essential activities*, to an expected increase in car use. Other paths start from an expected increase in *car ownership* (S1A3.1), an increase in the *attractiveness/willingness to use the car* (S1B3.1, S1B3.2, S1B3.3), or an increase in *urban sprawl* (S1D3.1, S1D3.2, S1D3.3). These paths are similar as paths identified for car dependency and car ownership. Figure 3 shows an example of the three paths starting from an increase in attractiveness of the car (see Table 4 for this reasoning behind this impact) and leading through the different paths to an increase in car use (S1B3.1, S1B3.2, S1B3.3).

In three of the 17 paths identified via the CLD, car use decreases. These paths all start with an expected *increase in congestion*. This can directly decrease *car use* (S1C3.1) or do this through a decrease in *attractiveness of the car* and subsequently a decrease in *car ownership* (S1C3.2) or a decrease in *car dependency* (S1C3.3)

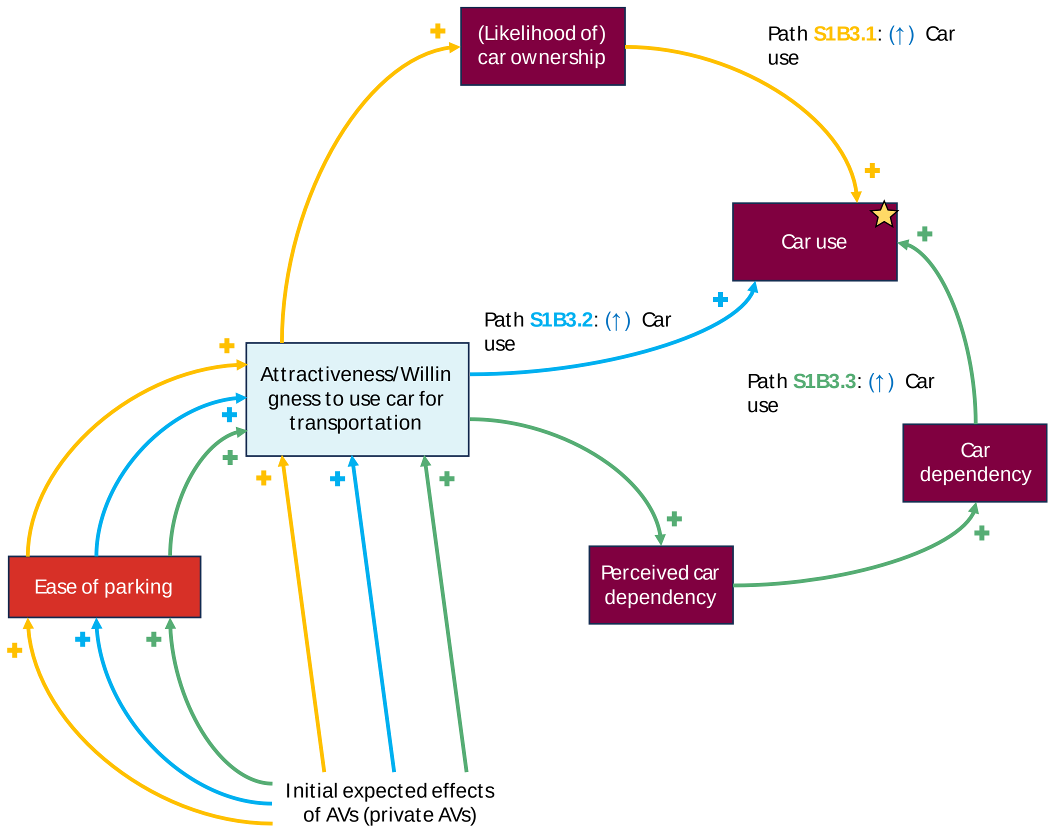


Figure 3. Examples of paths leading to an increase in car use, starting from expected changes in attractiveness/willingness to use car for transportation for private AVs scenario (based on Table 4) (paths S1B3.1,S1B3.2,S1B3.3). Star factor indicates factor of interest in this particular case, each path is represented by a different colour.

Overall expected impact of private AVs on car dependency, use, and ownership

Although the CLD analysis does not include quantification of the effects of this scenario, most of the identified impact pathways seem to lead to an increase in car dependency, car ownership, and car use. The only paths leading to a decrease of these three factors goes through an increase of congestion, which decreases the attractiveness of the car. This is part of a balancing feedback loop in the CLD (loop 2 in appendix 2). Therefore, the long-term effect of this increase in congestion might be limited (e.g. an increase in congestion leads to a decrease in car use, leading to a decrease in congestion). Also, this effect is partly counteracted by the path through an increase in car-oriented infrastructure investments which decreases congestion again (e.g. paths S1C3.4 and S1C3.6). Lastly, congestion might be mitigated by traffic management (see below).

Expert's expectations on the impact of private AVs on car use vary. Zijlstra did not expect a major increase in the number of kilometres travelled by people as long as travel time valuation would not drastically change. However, as time spent in the car can be used differently in AVs, this value of travel time might change. Jeekel followed this same reasoning with the expectation that this different use of time in the vehicle will allow people to move further away from their work, increasing the travelled kilometres – which is in line with the reasoning in the CLD analysis above (S1D3.1/S1D3.2/S1D3.3). The extent to which this impacts the traffic on the road depends on the adoption rate of private AVs. The same holds for the kilometres that empty AVs might travel, which can significantly add to the total kilometres travelled (Zijlstra).

4.1.2 Traffic management and policy impact of private AV scenario

Traffic management will need to play a role in mitigating the negative effects of the expected increases in car use, car ownership, and congestion. As discussed in section 3.1, next to the increase in vehicle kilometres from people travelling further, vehicle kilometres might also be increased by empty trips. This could especially occur with private AVs, mainly within urban areas. Existing parking policies aiming to reduce the cars in the city centre might not be effective anymore with private AVs that can drop owners in the city centre and then drive themselves to a parking spot. This increases the use of parking or road infrastructure in city centres as drop-off and pick-up locations. Parking policies need to be revised, both for inner city parking and for parking in the periphery – where idle AVs are likely to park until they are going to be used again.

The increase in vehicle kilometres outside the urban areas can be combatted by implementing innovative TM policies such as stimulating platooning of AVs and optimising traffic system-wide instead of every vehicle for itself. Note that these policies become more effective with more AVs on the road and a system optimum can only be reached with a minimum of 23% of the fleet being connected AVs (Chen et al., 2019).

As mentioned in the interview with Van Waterschoot (section 3.2), getting all AVs connected and adhering to TM instructions will require cooperation of public authorities and private sector parties such as car manufacturers and service providers. This is especially challenging in the private AV scenario, where all AVs are privately owned instead of a few parties managing and operating entire fleets of AVs – which would reduce the governance challenge to getting these few operators committed.

4.2 Shared Vehicle Scenario (robo-taxis)

The shared vehicle scenario explores a future in which AVs are widely available as on-demand door-to-door transport (robo-taxis). The use of this shared AV system is expected to largely depend on the cost (Zijlstra) and (reliability of) availability (Ettema). With a high availability against low costs, robo-taxis could be attractive to be used on a large scale. However, both Jeekel and Zijlstra raised the concern that such robo-taxis could cannibalise the demand for the current public transport (PT) system – mainly the bus services. A decrease in bus ridership might lead to marginalisation of the PT service. Zijlstra therefore calls for actively steering towards an inclusive, accessible, and collective AV system (see scenario 3 in section 4.3), since this can actually contribute to solving issues of current public transport systems such as rising costs and low service levels. Jeekel adds that when shared AVs (robo-taxis) are not cheap and available enough, only the higher income groups can benefit from them. In such a case, only the higher income groups shift from the bus to a robo-taxi and the lower income groups will face the PT service marginalisation and an even more decreased accessibility However, when they are very cheap, there is a risk of shared AVs cannibalising active mobility (Zijlstra).

4.2.1 Impact of shared vehicle scenario (robo-taxis) on factors of interest

Table 9 presents the overview of the impact of the shared vehicle scenario (robo-taxis) on car dependency, car ownership, and car use. Each factor of interest is further discussed below. See Appendix 3 for details on each impact (i.e. ((↑) Increase / (↓) Decrease).

Table 9. Consolidated expected effects of shared AV scenario (robo-taxis) on factors of interest (see Appendix 3 for details)

Factor of interest	*Consolidated expect effect (see Appendix 3 for details)*	
Car dependency	11 paths (↑) Increase	5 path (↓) Decrease
Car ownership	10 paths (↑) Increase	4 path (↓) Decrease
Car use	23 paths (↑) Increase	11 paths (↓) Decrease

Car dependency

Sixteen paths have been identified from the factors influenced by the shared AV (robo-taxi) scenario (see Table 5) towards car dependency. These show how this scenario can be expected to affect car dependency, either increasing or decreasing. Eleven of these paths indicate an expected increase in car dependency, while five indicate an expected decrease.

The five paths leading to an expected decrease in car dependency all start with a change in congestion. Four of them (S2B1.7/S2B1.8/S2B1.9/S2B1.10) start with the expected *decrease in congestion* in this scenario and all follow a path through expected decrease of *investments in car-oriented infrastructure*. For paths S2B1.7 and S2B1.8, the reduction in investments in car-oriented infrastructure then leads to an increase in the *attractiveness of cycling or using the public transportation*, which eventually leads to a decrease in perceived car dependency and car dependency. For paths S2B1.9 and S2B1.10, in turn, a reduction in investments in car-oriented infrastructure leads to a decrease in urban sprawl, distance to essential activities/opportunities, and ultimately objective car dependency and car dependency. The fifth path (S2B1.1) starts with an expected *increase in con-*

gestion, decreasing the *attractiveness/willingness to use the car* and leading to a reduction in perceived car dependency and ultimately car dependency. As an example of how these paths go through the CLD, the five paths leading to an expected decrease in car dependency are shown in Figure 4. In this figure, all paths start with the expected direct impact of this shared AV scenario on the factor congestion (see the tables in section 2.5 for an explanation of all expected direct effects of the different scenarios).

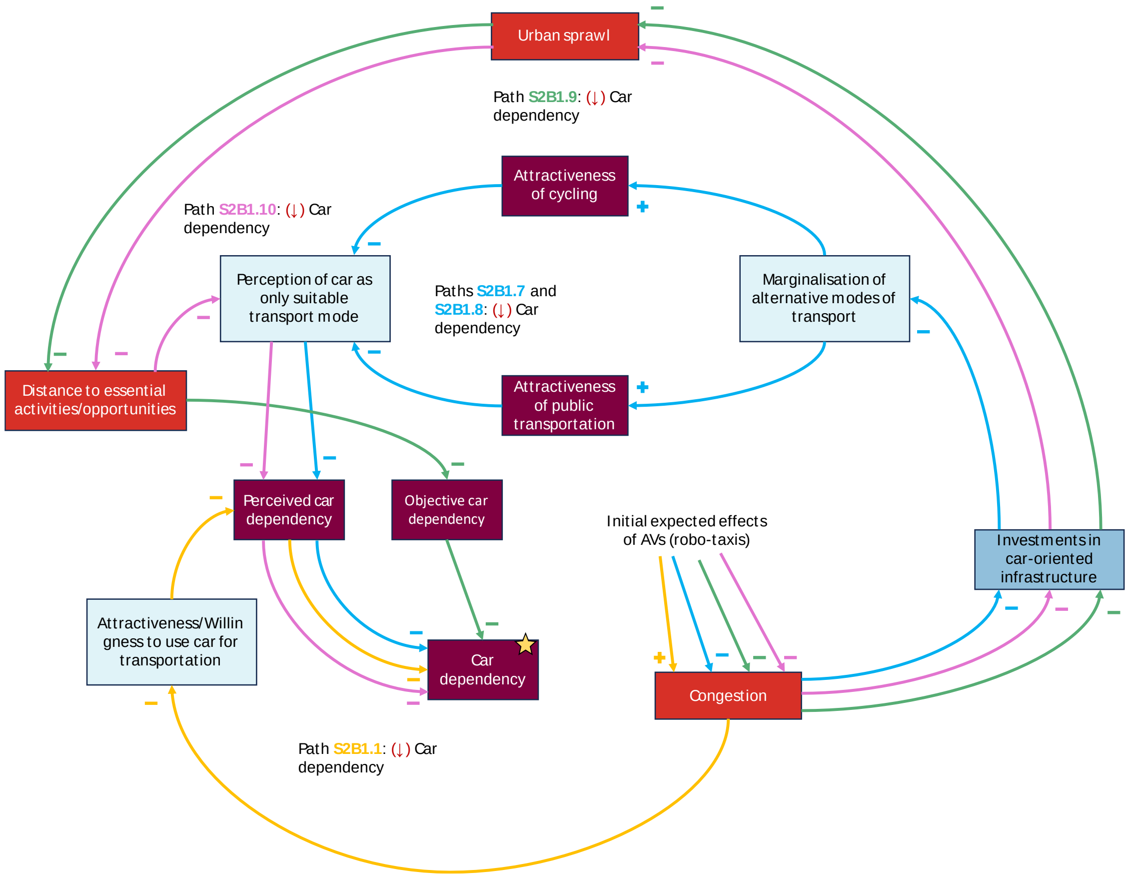


Figure 4. Examples of paths leading to a decrease in car dependency, starting from changes in congestion that are expected in the robo-taxis scenario (based on Table 5) (paths S2B1.1, S2B1.7, S2B1.8, S2B1.9, S2B1.10). Star factor indicates factor of interest in this particular case.

Four paths leading to an increase in car dependency follow a similar path from an expected *increase in congestion* (see Table 5 in section 2.5), through *investments in car-oriented infrastructure*, leading in various ways to an increase in car dependency (S2B1.2/S2B1.3/S2B1.4/S2B1.5). Other paths leading to an expected increase in car dependency start from the expected increase in *attractiveness/Willingness to use car for transportation* (S2A1.1), an expected increase in *urban sprawl* (S2C1.1/S2C1.2), an expected decrease in *car-related costs* (S2D1.1), and expected decreases in *attractiveness of cycling and public transport* (S2E1.1/S2F1.1).

Car ownership

Fourteen paths have been identified from the factors influenced by the shared AV (robo-taxi) scenario (see Table 5) towards (the likelihood of) car ownership. Of these paths, four are expected to lead to a decrease in car ownership, and ten are expected to lead to an increase. The paths leading to an expected decrease in car ownership all start with a change in congestion – some with an expected increase in congestion (path S2B2.1), others with an expected decrease (paths S2B2.6, S2B2.7, S2B2.8) (see Appendix 3 for details). Similarly to the paths described for car dependency earlier in this scenario (and in Figure 4), three of these paths (S2B2.6, S2B2.7, S2B2.8) go from the *decrease in congestion*, through a decrease in *investments in car-oriented infrastructure*, in various ways to an expected decrease in car ownership. The last path to a potential decrease in car ownership starts at an expected *increase in congestion* and goes through a decrease in *attractiveness of the car* to a decrease in car ownership (S2B2.1).

An increase in car ownership is expected through an expected increase in the *attractiveness to use the car* (path S2A2.1). From an expected *increase in congestion*, through an increase in *investments in car-oriented infrastructure*, multiple other paths (S2B2.2, S2B2.3, S2B2.4) lead to an expected increase in car ownership. Another expected impact path (S2B2.5) goes from an expected *decrease in congestion* through an increase in *attractiveness of the car*, to an expected increase in car ownership. The last paths towards an increase in car ownership start from an expected increase in *urban sprawl* (S2C2.1), an expected decrease in *car-related costs* (S2D2.1/S2D2.2), and expected decreases in *attractiveness of cycling and public transport* (S2E2.1/S2F2.1).

Car use

The expected effect of this scenario on car use can be described by following 34 different impact paths. 23 of these paths lead to an expected increase in car use, while 11 lead to an expected decrease.

Nine out of 23 paths leading to an expected increase in car use start with an expected change in congestion. Some start from an expected *decrease in congestion* and lead through an expected increase in *attractiveness of the car* to an increase in car use (S2C3.10/S2C3.11/S2C3.12). Others start from an expected *increase in congestion*, and lead through an increase in *investments in car-oriented infrastructure* to an increase in car use (S2C3.4/S2C3.5/S2C3.6/S2C3.7/S2C3.8/S2C3.9). Other paths increasing car use start from an expected increase in *attractiveness/willingness to use the car* (S2B3.1/S2B3.2/S2B3.3), an expected increase in *urban sprawl* (S2D3.1/S2D3.2/S2D3.3), an expected decrease of the *attractiveness of cycling and public transportation* (S2E3.1/S2E3.2/S2F3.1/S2F3.2), or an expected decrease of *car related costs* (S2G3.1/ S2G3.2/ S2G3.3/ S2G3.4).

The first path leading to a decrease in car use is the expected direct impact of this scenario on the *car ownership*, which leads to a decrease in car use (path S2A3.1). Next, there are seven different paths from a *decrease in congestion*, through a decrease in *investments in car-oriented infrastructure*, to a decrease in car use (S2C3.13/S2C3.14/S2C3.15/S2C3.16/S2C3.17/ S2C3.18/S2C3.19). Also the expected *increase in congestion* can lead to a decrease in car use through a decrease in the *attractiveness of the car* (S2C3.1/S2C3.2/S2C3.3).

Overall expected impact of shared AVs (robo-taxis) on car dependency/use/ownership

Most expected impact on car dependency, use and ownership was seen as an effect of the expected change in congestion. Both expected increases and decreases in congestion seem to lead to effects on car dependency, car use, and car ownership. Through these impacts, the three factors of interest sometimes see an expected decrease and sometimes an expected increase. Because of this, it depends on the order of magnitude of the expected direct impact of section 2.5 (e.g. increase or decrease in congestion) whether the overall impact will be an increase or decrease of car dependency, use, and ownership. Also the second order effects in the CLD become more relevant. Congestion is often part of reinforcing feedback loops, especially when considered in combination with investments in car-oriented infrastructure, leading to potentially very strong multi-order effects if all else remains the same (see loops 5, 10, 11, 13 in appendix 2). As mentioned in the results above, this can also affect the attractiveness of public transport and cycling significantly. Intervention somewhere in these loops – e.g. preventing extra investments in car-oriented infrastructure are done every time in this reinforcing loop – might prevent or mitigate these stronger multi-order effects.

The marginalization of alternative transport modes as a results of car-oriented infrastructure investments takes place in multiple of the mentioned impact paths of this scenario. This was also why Zijlstra and Jeekel expressed recommendations in their interviews: it would be wise to steer AV implementation towards an inclusive, publicly accessible, collective system. This could prevent shared AVs such as robo-taxis from cannibalising the current public transport system and leading to a marginalization of this system. Shared robo-taxis would then not only service higher-income groups and not negatively impact the accessibility of lower-income groups – which would be even more of an issue with the expected increases in urban sprawl as the distance to amenities increases (Ettema). Both marginalization of other modes and urban sprawl only see a decrease in the impact paths in the CLD when investments in car-oriented infrastructure decreases. Ensuring this would require policy interventions, as was also mentioned by Jeekel and Ettema. Similarly, Jeekel expected a decrease in car ownership in this shared AV scenario (in line with some of the paths in the CLD). However, other impact paths show that car ownership could also go up, which supports the claimed need for policy interventions on this topic by Ettema.

4.2.2 Traffic management and policy impact of shared AV (robo-taxi) scenario

Similarly as with the private AV scenario, traffic management will need to play a role in mitigating negative effects of expected increases in car use, car ownership, congestion. Although because the overall impacts still remain ambiguous, the extent to which this requires increased attention of the traffic management domain remains unclear. What can be reasoned, however, is that where the private AV scenario saw parking issues and most empty kilometres would be from destinations to parking locations, the shared AV scenario with robo-taxis will see different issues. The empty kilometres of robo-taxis will occur in between trips with passengers. Therefore, they are likely to mainly occur between (high demand) destinations. Idle waiting or driving around will also occur near high-demand locations. Traffic management policies will be required to mitigate these extra kilometres in high-demand and often busy areas.

As mentioned above, other policy interventions are required to increase the chance that the presence of robo-taxis in this scenario can actually lead to a decrease in car ownership. Ettema stressed that restrictive policies on car ownership should only be implemented if the alternative – the shared AV system in this scenario – is good enough. Therefore, availability and reliability of shared AVs should be high enough. This could ask for dedicated AV lanes as discussed in section 3.1, as these can help improve overall AV attractiveness.

The governance of fleets of shared AVs can be less complex than in the private AV scenario, since in this scenario, larger fleets of AVs might be managed by a limited number of operators. Ensuring adherence of these fleets of AVs to traffic management instructions can be done by getting commitment of a limited number of stakeholders, instead of having to get commitment of all individual users. This commitment could be even more easily be enforced when an operating license with conditions is implemented for shared AV operators. Users might also be more accepting of their robo-taxi taking a system-optimum route instead of a user-optimum route than when their private vehicle would do that.

4.3 Shared AV Scenario (robo-buses)

The shared AV (robo-bus) scenario considers a future in which AVs are widely available as on-demand transport for shared rides, practically functioning as automated buses. This shared AV system might complement existing public transport, especially in low-demand areas where a bus service might not be financially feasible due to high costs – mainly due to costs of drivers (Zijlstra). Also in higher-demand urban areas, the robo-buses might be useful as feeders to main public transport hubs (Jeekel).

4.3.1 Impact of shared vehicle scenario (robo-buses) on factors of interest

Table 10 presents the overview of the impact of the shared vehicle scenario (robo-buses) on car dependency, car ownership, and car use. Each factor of interest is further discussed below. See Appendix 3 for details on each impact (i.e. ((↑) Increase / (↓) Decrease).

Table 10. Consolidated expected effects of shared vehicle scenario (robo-buses) on factors of interest (see Appendix 3 for details)

Factor of interest	*Consolidated expect effect (see Appendix 3 for details)*	
Car dependency	3 paths (↑) Increase	8 path (↓) Decrease
Car ownership	2 paths (↑) Increase	6 path (↓) Decrease
Car use	6 paths (↑) Increase	15 paths (↓) Decrease

Car dependency

Eleven paths have been identified from the factors influenced by the shared AV (robo-buses) scenario (see Table 6) towards car dependency. These show how this scenario can be expected to affect car dependency, either increasing or decreasing. Eight of these paths indicate an expected decrease in car dependency, while three indicate an expected increase.

The robo-buses scenario show an important difference when compared to the previous two scenarios, as it depicts the majority of the consolidated effects on car dependency (but also car ownership and car use) being a decrease in the factor of interest. From the eight paths leading to an expected decrease in car dependency, four start with an expected *decrease in congestion* and *investments in car-oriented infrastructure* (S3A1.2/S3A1.3/S3A1.4/S3A1.5), which then follow through *increase in the attractiveness of cycling and public transportation* (S3A1.2/S3A1.3), or through a *reduction in urban sprawl* (S3A1.4/S3A1.5), until ultimately reaching a *reduction in car dependency*. The other four paths leading to an expected reduction in car dependency (S3C1.1/S3C1.2/ S3D1.1/S3E1.1) operate via non-car related variables. By means of an expected *reduction in the cost of public transportation*, car dependency decreases via a *reduced objective car dependency* (S3C1.2), and via an *increase in the attractiveness of public transportation*, followed by a *decrease in the perceived car dependency* (S3C1.1). With an expected *increase in the attractiveness of public transportation* and *attractiveness of cycling*, the *perception of car as only suitable transport mode* also gets reduced, ultimately reducing *perceived car dependency* and *car dependency*.

The three paths leading to an expected *increase in car dependency* (S3A1.1/S3B1.1/S3B1.2) operate via an expected *decrease in congestion* – which lead to an *increase in the attractiveness of using the car*, and consequently an *increase in car dependency* (S3A1.1) –, and via an *increase in urban sprawl*, which *increases the distance to essential activities*, and ultimately *increases car dependency* via objective (S3B1.1) or subjective (S3B1.2) car dependency.

Car ownership

Eight paths have been identified from the factors influenced by the shared AV (robo-buses) scenario (see Table 6) towards car ownership. These show how this scenario can be expected to affect car ownership, either increasing or decreasing. Six of these paths indicate an expected decrease in car dependency, while two indicate an expected increase. The six decreasing paths have been illustrated in Figure 5.

Car ownership can be expected to decrease via reductions in congestion (S3A2.2/S3A2.3/S3A2.4) and cost of public transportation (S3C2.1), and increases in the attractiveness of cycling and public transportation (S3D2.1/S3E2.1). Figure 5 provides a visual explanation how these paths operate until reaching car ownership. With an expected *decrease in congestion* and *investments in car-oriented infrastructure*, the *attractiveness of public transportation and cycling are expected to increase*, reducing the *perception of the car as the only suitable transportation* mode, and ultimately *reducing car use* (S3A2.2/S3A2.3). A *decrease in congestion* is also expected to reduce car ownership via a reduction in investments in car-oriented infrastructure and a reduction in urban sprawl (S3A2.4). An expected *decrease in the cost of public transportation* leads to an *increase in the attractiveness of public transportation* (S3C2.1), which together with an *increase in the attractiveness of cycling* lead to a *reduction in the perception of the car as the only suitable transportation* mode and ultimately *reducing car use* (S3D2.1/S3E2.1).

Two paths were identified through which an increase in car ownership can be expected. Through the expected *decrease in congestion*, the *attractiveness of the car* can increase, leading to an increase in car ownership (S3A2.1). Secondly, due to the expected increase in *urban sprawl*, distances to essential activities will increase. This can lead to an increase in the *perception of the car as the only suitable mode of transport*, leading to an increase in car ownership (S3B2.1).

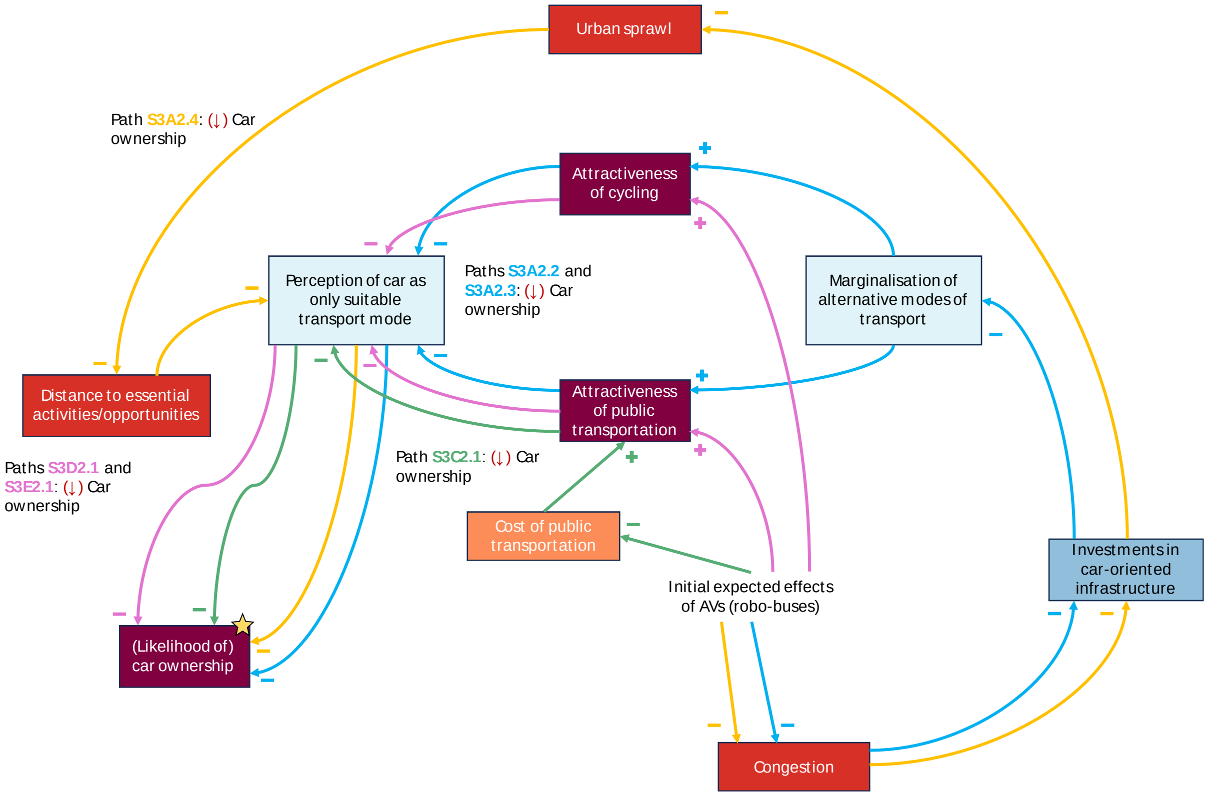


Figure 5. Examples of six paths leading to a decrease in car ownership resulting from changes in congestion, cost of public transportation and attractiveness of cycling and attractiveness of public transportation for robo-buses scenario (based on Table 6) (paths S3A2.2,S3A2.3,S3A2.4,S3C2.1, S3D2.1,S3E2.1). Star factor indicates factor of interest in this particular case.

Car use

In the shared AV robo-buses scenario, six paths have been identified to lead from an expected direct impact of this scenario (see Table 6) to an increase in car use, while fifteen paths have been identified to lead to a decrease in car use. Half of the paths expected to increase car use start from an expected *decrease in congestion* and lead via an increase in the *attractiveness/willingness to use the car* to an increase in car use (S3B3.1/S3B3.2/S3B3.3). The other half of the paths leading to an increase in car use in this scenario start with an expected *increase in urban sprawl*. Through an increased *dis-*

tance to essential activities/opportunities, this leads to increases in objective or subjective car dependency (respectively paths S3C3.1 and S3C3.3) or an increase in car ownership (S3C3.2), which all leads to an increase in car use.

Almost half of the paths leading to a decrease in car use in this robo-bus scenario are already extensively covered above: a *decrease in congestion* leading, through a decrease in *investments in car-oriented infrastructure*, to a decrease in car use (S3B3.4/S3B3.5/S3B3.6/S3B3.7/S3B3.8/S3B3.9/S3B3.10). Unique to this scenario are the paths leading from an expected decrease in the *cost of public transportation*, through an increased *attractiveness of public transportation* (S3D3.1/S3D3.2) or a decrease in *objective car dependency* (S3D3.3), to a decrease in car use. Also the paths starting from an expected increase in *attractiveness of cycling* (S3E3.1/S3E3.2) and *attractiveness of public transportation* (S3F3.1/S3F3.2) are unique to this scenario. These four paths follow similar routes through the CLD: they lead to a decrease in the *perception of car as only suitable transport mode* and go through either a decrease in *car ownership* (S3E3.1/S3F3.1) or a decrease in *car dependency* (S3E3.2/S3F3.2) to a decrease in car use. Lastly, there is a path from an expected direct negative impact on *car ownership* to an expected decrease in car use (S3A3.1).

Overall expected impact of shared AVs (robo-buses) on car dependency/use/ownership
Contrary to the first two scenarios, the shared AV – robo-bus scenario shows for all three factors of interest more decreasing paths than increasing paths. This difference can be explained by looking at the expected direct impacts of this scenario. Next to the decrease in congestion that is also part of many impact paths in the other scenarios, this scenario has expected direct impacts on the attractiveness and cost of public transportation, and the attractiveness of cycling. These impacts start more paths leading to a decrease in car use, car ownership, and car dependency. The attractiveness of the private car is not directly affected in this scenario, but a relative decrease is expected because of the increase in attractiveness of alternative transport modes.

The interviewed experts also expected this effect. They stated that in this scenario, AVs could be embedded in the public transport system and could actually complement existing public transport, especially in rural areas (Zijlstra, Ettema). The main role of these robo-buses could be to serve as local feeders for existing major public transportation lines (Jeekel, Ettema). An implementation question that was raised is whether these AVs should provide door-to-door transport or use a network of fixed stop locations for the on-demand service. The latter would decrease the amount of infrastructure that needs to be upgraded in order to accommodate the SAE-level 4 and 5 AVs (Zijlstra).

4.3.2 Traffic management and policy impact of shared AV (robo-bus) scenario

This scenario could result in a decrease in car use and due to the assumed widespread adoption of shared AVs for collective rides – and thus with a higher-than-average occupation rate – the number of vehicles on the road could decrease. Although it remains difficult to quantify the expected effect on traffic – also considering the potential empty kilometres of these robo-buses – it is possible that traffic intensities could decrease. If this system is mainly implemented as local transport and as feeder system for existing major public transport lines (e.g. inter-city trains), then the potential extra (empty) kilometres of these AVs are likely to mainly occur on local roads, both in cities and in rural areas. However, if these replace private car use, the impact on the traffic intensities might still be positive. Due to the increased attractiveness of public transport, the expected decrease in car use could then also be visible in the traffic intensities on highways.

Decreasing car use and decreasing traffic volumes on roads might also decrease the pressure on traffic management, giving more room for reaching various traffic management goals (e.g. throughput and accessibility, but also environmental and other societal goals). Simultaneously, the traffic that is on the road, and that might actually see an increase in vehicle kilometres, will be the shared AVs. These AVs provide new traffic management opportunities as discussed in chapter 3. This might even more increase the ability of traffic management to contribute to reaching those goals.

In this scenario, however, the governance might be very complex. In order to reach the decrease in car use, car ownership and car dependency that seems possible according to the above analysis, the AVs in this scenario should serve as local public transport and as feeders for other public transport lines. Therefore, public sector involvement is likely to be required (Van Waterschoot). This raises the question whether this scenario of AV deployment in the form of robo-buses could be a commercial service or should be a public service. The latter could be arranged by governments taking a leading role in this, either by state-owned operators, or by implementing concessions as seen with conventional public transport. Both would require significant investments of time and resources to achieve.

5 Conclusion

Automated driving is expected to play a vital role in our future mobility system and there are several indications that we could be headed towards a future where the use of automated vehicles becomes the norm, and more vehicle-kilometres are driven with these types of vehicles. In such scenarios, current traffic management strategies and policies will have to be redefined to accommodate the new reality on the road. The expected changes brought by the introduction of AVs into the traffic system are non-trivial and will require the relevant stakeholders to carefully consider the wider implications for the mobility system and policy goals. To this end, this challenge examined the issue of car dependency and traffic management in the era of automated driving. Based on the literature review and expert interviews, a causal loop diagram (CLD) was developed and used to analyse how car dependency could change when automated driving is present on a large scale and the expected impact of automated vehicles (AVs) on traffic management (TM) policies during this era. The analysis was based on three hypothetical scenarios of automated driving implementation namely privately owned AVs, shared AVs for private rides (e.g. robo-taxis), and shared AVs for collective rides (e.g. automated buses). Within each scenario, we also investigated to what extent any changes in car dependency (increase or decrease) will have an effect on traffic management.

5.1 Main Findings on Automated Driving and Car Dependency

What is car dependency? When do people experience car dependency and when do they actually depend on the car?

Literature review and expert interviews showed that car dependency mainly describes the extent to which someone depends on the car as a mode of transport, and this can be both objective and subjective in nature. Objective car dependency refers to more measurable factors such as the availability and the costs of alternative transport options or the distance to essential amenities. On the other hand, factors such as mobility habits, the feeling of empowerment experienced by owning a car and one's car-related identity are classified as subjective car dependency.

How does automated driving influence the choice of alternatives to the (private) car and how does it change the degree of car dependency?

The influence of automated driving on car dependency varies based on the considered scenarios of implementation. The CLD analysis revealed that in the private AV scenario most paths lead to increase in car-dependency. An example of a path to increase in car-dependency in this scenario is the increase in the attractiveness of the car due to the ability to spend time more productively in a private AV. This productive use of time makes people more comfortable living further away from their work (or accept more driving time) which in turn makes them car-dependent (either objectively due to distance or subjectively due to their perception of driving time). On the other hand, the CLD only contains a few paths that lead to a decrease in car dependency and these paths are part of a balancing feedback loop. This means that their long-term effect on car dependency could balance out and they would not continue to reduce them. As an example, car-dependency is reduced if the attractiveness of the car decreases due to too much congestion on the road. However, this decrease is contingent on the reduction of extra investment in car-oriented infrastructure to alleviate the congestion (such as building new roads or offering better traffic management). Therefore, additional government policies supporting more investment in public transport infrastructure than investments in car-oriented infrastructure would need to be designed in order to prevent this effect on car dependency from being balanced out in the long term.

The shared AV scenario (robo-taxi) showed more balance between increasing and decreasing paths towards car use, car ownership and car dependency than in private AV scenario. However, still many more increasing paths than decreasing paths could be identified for car ownership and car dependency. A noteworthy outcome of this scenario is the potential marginalization of alternative transport modes such as public transport and cycling. This was also confirmed in the interviews with experts. Most paths in this scenario lead to an increase in car-oriented infrastructure investments mainly caused by an expected increase in congestion. These car-oriented investments are likely to have a negative impact on investments in other modes of transport and might therefore lead to an increase in car dependency. To combat this, policies need to be put in place to discourage or decrease spending on car-related infrastructure in favour of other modes of transport. Finally, if the cost of a ride is high, these shared AVs will mainly service higher-income groups and this scenario may have a negative impact on the accessibility of low-income groups. A combination of high cost of shared AVs with a lack of investment in public transport may lead to marginalization of public transport, disproportionally affecting low-income groups. In this case policies need to be put in place to regulate prices or provide subsidies for these affected group.

The main conclusion from both the private and shared AVs scenario is that most paths lead to increase in car dependency and car-use – which seems concerning given the potential effects of increases in car dependency and car use. In both scenarios, the government may need to take quite severe measures to combat this increase. An example of such measures could be limiting or banning car use at certain times and locations combined with increased investment in alternative modes of transport such as public transport, cycling and walking.

In the shared AV (robo-bus) scenario, there are more decreasing paths than increasing paths for car dependency, car ownership, and car use. Unlike the private and shared AV scenarios, the robo-bus can be used to complement or upgrade the current public transport system - especially local buses. In this scenario, the attractiveness of public transport is expected to increase if costs of rides are low, and the service is reliable and available in high frequency in many locations. The combination of reduced costs and increased accessibility could lead to a decrease in car dependency especially for low- and medium-income groups. Finally, robo-buses could help to reduce congestion since they are expected to have a far higher vehicle occupancy rate (comparable to a bus) than private AVs and robo-taxis. Their potential to reduce congestion might encourage more government investment in public transport thereby increasing its attractiveness which leads to decrease in car dependency.

The main conclusion from the robo-bus scenario is that it has many paths leading to reduction in car dependency. However it is expected that public authorities may need to incur extra costs both in infrastructure investment and subsidies in this scenario. The magnitude of the cost will depend on how the service is provided – whether in form of concessions with robo-bus operators or completely owned and run by the government. We foresee that special policy instruments need to be designed to support reliable, equitable and sustainable operation of the service.

5.2 Main Findings on Automated Driving and Traffic Management

How will automated driving change traffic management, the amount of car kilometres driven (freight/personal) and the accessibility of activities?

In general, there are some expected changes in traffic management strategies and policies with AVs. One potential change is the level of control as AVs are expected to be more compliant with traffic control strategies. This will give traffic managers more direct influence on traffic than they have on human-driven vehicles (HDVs) and also allow for new TM control opportunities such as route advice, automatic lane allocation and traffic signal optimisation.

In the private AV scenario, the CLD analysis and interviews with experts point towards a potential increase in car kilometres because of their ease of use (convenience) and the possibility to perform activities during the trip. The extra car kilometres will be mostly driven by people who moved further away from work or those who now find it more convenient to use the car. Apart from this, an additional increase in car kilometres is expected in urban areas due to empty trips of AVs driving towards (or searching for) a parking location. This same effect is expected with the robo-taxi scenario, where empty trips are likely to occur between passenger trips, mainly in high-demand areas.

What role can traffic management play in achieving policy goals in a context of automated driving?

In the private AV and robo-taxi scenarios, traffic management will need to play a role in mitigating the expected increase in car kilometres and congestion. In addition, parking policies need to be revised, both for inner city parking and for parking outside the city for example at locations where idle AVs will park themselves. In both scenarios, the role of traffic management could be that of an orchestrator who optimizes traffic to achieve system optimum policy goals of delay, throughput, emissions and safety. For example, in urban areas, AVs can communicate their position, speed and planned route to traffic managers to optimize the traffic signal cycle and also information of traffic signal cycle lengths and green times can be shared with AVs to help them optimize their route and speed. Traffic management can also play a role in defining parking policies for AVs. For example by setting duration of parking at various locations and time. Van den Hurk et al. (2020) suggest AV parking policies that favour local parking for short durations and remote parking for longer durations to limit the number of empty kilometres driven.

Finally, the role of traffic management in the robo-buses scenario is expected to be much limited compared to the private and shared scenario because the service and management will be similar to that of public transport.

What is required for this in terms of development, data, and organization?

For a successful implementation of AVs for the benefit of traffic management, a solid traffic management plan is required. This plan will require strong coordination between AV manufacturers, road authorities, government bodies, service providers and other involved parties. The plan should include agreements on data storage, data formats, standard information that AVs should communicate to TM control, standard information that should be communicated to AVs, standard types of TM instructions that can be given to AVs in certain situations, and the expected response of AVs to these instructions. These requirements can be challenging to achieve but are needed for a successful implementation. In the shared AV scenario, ensuring adherence of these fleets of AVs to traffic management instructions can be done by getting commitment of the operators. This commitment could even more easily be enforced when an operating license with conditions is implemented for shared AV operators. For equitable deployment of shared AVs, government involvement is likely to be inevitable as commercial deployment is most likely focused on high-demand areas and not on rural areas – where these AVs could play a crucial role in improving accessibility.

5.3 Limitations of Research

This quick scan analysis revealed some possible directions of the effects of automated driving on car dependency and traffic management. However there are some limitations of the current analysis that should be discussed. First, it is important to note that our analysis only revealed direction of the effects. The magnitude of the effects of each factor in all the scenarios is highly dependent on the adoption rate of the type of AVs present in that scenario. For example in the shared AV scenario, large scale deployment and use of the shared AV will only occur if the cost of a ride is affordable, and the service is reliable and available in many locations for a significant proportion of the population. The same holds for the private AVs scenario. If private AVs are too expensive and can only be afforded by a privileged few, then the magnitude of the expected effects both on car dependency and traffic management will be greatly reduced.

The second limitation of our research is that the (order of) magnitude of the identified effects is unknown. For each scenario, only the total number of paths increasing or decreasing car dependency were identified, but the magnitude of the increase or decrease is not known. To reach a final conclusion whether the expected effect is overall positive or negative, we assumed that both the increase and decrease have the same weight. So when there are clearly more increases than decreases then we conclude that the path is likely to be an increase (and vice-versa). When the number of increases and decreases are evenly distributed (almost the same) then it is not possible to reach a conclusion. In most cases, the assumption of equal weights may not hold. Therefore, more in-depth analysis is required to reach a final conclusion on the expected effects.

Finally, this report is a quick-scan analysis and is thus limited in scope to the hypothetical scenarios, definitions and assumptions used in the report. It does not cover in-depth other important aspects of car dependency and automated driving such as equity, transport poverty and traffic safety.

5.4 Overall conclusion and future outlook

The quick scan analysis in this report revealed many paths via which car dependency, car ownership and car use could increase, especially in the scenarios of private AVs and robo-taxis. This means some quite severe traffic management and policy measures might be needed to cope with the new realities on the road and to mitigate the negative effects related to car use and car-dependency.

Only in the robo-bus scenario, there was more balance between paths leading to increases and decreases of car dependency, car ownership and car use. However, this type of AV deployment would also require more policy interventions and active government involvement to be realised.

To help stakeholders and policy makers prepare and make sound policies on this issue, more research is needed to substantiate the findings in this report. In the future, it would be worthwhile to explore the causal loop diagram of car dependency and automated driving in more detail (perhaps with involvement of a larger group of experts with different backgrounds), and look for data with which the impact of the different paths can be quantified (e.g. in data sets or through surveys or expert judgment). We hope that this report will provide policy makers and other relevant stakeholders a good starting point for a more in-depth analysis and discussions on the topic.

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Appendix 1: Mapping of factors and references in CLD

Origin factor	Destination factor	Direction of change (Origin factor → Destination factor)	Description
Availability of disposable income	car ownership	Increase	Based on Muñoz et al. (2024)
Household size	car ownership	Increase	Based on Muñoz et al. (2024)
Household working members	car ownership	Increase	Based on Muñoz et al. (2024)
Perception of car as only suitable transport mode	car ownership	Increase	Proposed by authors
Driving aversion	car ownership	Decrease	Based on Helferich et al. (2024)
Car related empowerment	car ownership	Increase	Based on Helferich et al. (2024)
Car oriented identity	car ownership	Increase	Based on Helferich et al. (2024)
Attractiveness/Willingness to use car for transportation	car ownership	Increase	Proposed by authors based on Helferich et al. (2024)
Car related costs	car ownership	Decrease	Proposed by authors based on Weir et al. (2024)
Ease of parking	car ownership	Increase	Proposed by authors based on Zijlstra et al. (2022)
Possession of driving license	car ownership	Increase	Based on Kampert et al. (2018)
Quality of walking and cycling infrastructure	Attractiveness of cycling	Increase	Proposed by authors
Awareness of health and environmental benefits of reducing car use	Attractiveness of cycling	Increase	Based on Weir et al. (2024)
Marginalisation of alternative modes of transport	Attractiveness of cycling	Decrease	Based on Zijlstra et al. (2022)
Feeling of insecurity while cycling	Attractiveness of cycling	Decrease	Proposed by authors

Origin factor	Destination factor	Direction of change (Origin factor → Destination factor)	Description
Awareness of health and environmental benefits of reducing car use	Attractiveness of public transportation	Increase	Based on Weir et al. (2024)
Marginalisation of alternative modes of transport	Attractiveness of public transportation	Decrease	Based on Zijlstra et al. (2022)
Feelings of insecurity in public transport	Attractiveness of public transportation	Decrease	Proposed by authors based on question in National Safety Monitor from CBS
Travel allowance benefits	Attractiveness of public transportation	Increase	Based on Zijlstra et al. (2022)
Cost of public transportation	Attractiveness of public transportation	Decrease	Proposed by authors based on Weir et al. (2024)
Availability of public transportation stops	Attractiveness of public transportation	Increase	Proposed by authors
Driving aversion	Attractiveness/Willingness to use car for transportation	Decrease	Based on Helferich et al. (2024)
Car related empowerment	Attractiveness/Willingness to use car for transportation	Increase	Based on Helferich et al. (2024)
Car oriented identify	Attractiveness/Willingness to use car for transportation	Increase	Based on Helferich et al. (2024)
Congestion	Attractiveness/Willingness to use car for transportation	Decrease	Based on Pokharel et al. (2023)
Car oriented mobility habits	Attractiveness/Willingness to use car for transportation	Increase	Proposed by authors based on Helferich et al. (2024) and Weir et al. (2024)
Car related costs	Attractiveness/Willingness to use car for transportation	Decrease	Proposed by authors based on Weir et al. (2024)
Ease of parking	Attractiveness/Willingness to use car for transportation	Increase	Proposed by authors based on Zijlstra et al. (2022)

Origin factor	Destination factor	Direction of change (Origin factor → Destination factor)	Description
Company car benefits	Attractiveness/Willingness to use car for transportation	Increase	Proposed by authors based on Zijlstra et al. (2022)
Objective car dependency	Car dependency	Increase	Proposed by authors
Car-oriented mindset and preferences	Car oriented mobility habits	Increase	Based on Weir et al. (2024)
car ownership	Car use	Increase	Based on Pokharel et al. (2023)
Road capacity	Car use	Increase	Based on Pokharel et al. (2023)
Car dependency	Car use	Increase	Proposed by authors
Attractiveness/Willingness to use car for transportation	Car use	Increase	Proposed by authors based on Weir et al. (2024)
Car use	Car use related emissions	Increase	Proposed by authors
Quality of walking and cycling infrastructure	Car-oriented mindset and preferences	Decrease	Based on Weir et al. (2024)
Car use	Car-oriented mindset and preferences	Increase	Based on Weir et al. (2024)
Car use related emissions	Climate change effects	Increase	Proposed by authors
Road capacity	Congestion	Decrease	Based on Pokharel et al. (2023)
Public transportation policies	Cost of public transportation	Decrease	Proposed by authors based on Pokharel et al. (2023)
Urban sprawl	Distance to essential activities/opportunities	Increase	Proposed by authors based on Pokharel et al. (2023)
Climate change effects	Environmental policies and legislations	Increase	Based on Weir et al. (2024)
Congestion	Investments in car-oriented infrastructure	Increase	Based on Pokharel et al. (2023)
Investments in car-oriented infrastructure	Marginalisation of alternative modes of transport	Increase	Based on Pokharel et al. (2023)
Quality of walking and cycling infrastructure	Objective car dependency	Decrease	Proposed by authors

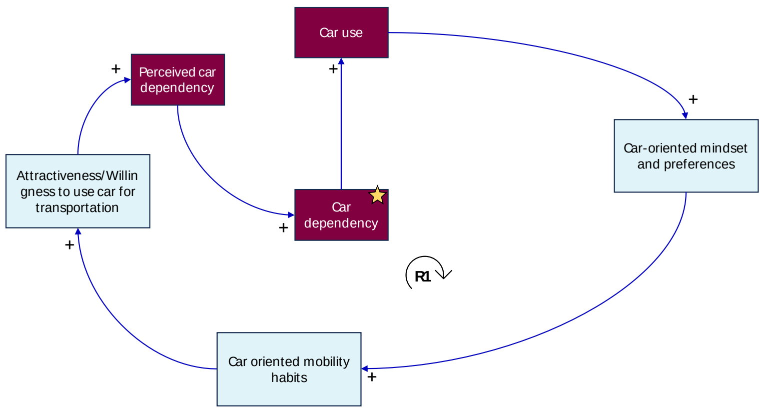
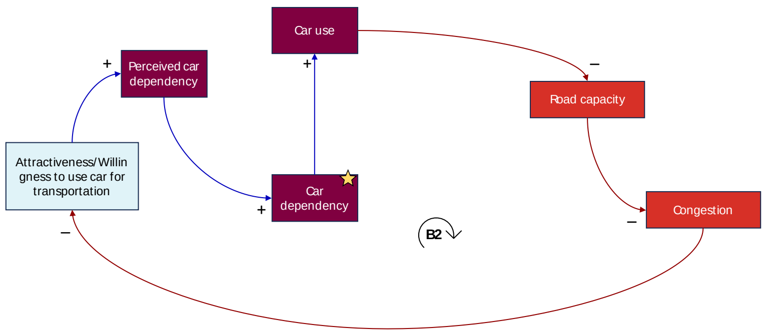
Origin factor	Destination factor	Direction of change (Origin factor → Destination factor)	Description
Distance to essential activities/opportunities	Objective car dependency	Increase	Proposed by authors
Cost of public transportation	Objective car dependency	Increase	Proposed by authors
Availability of public transportation stops	Objective car dependency	Decrease	Proposed by authors
Perception of car as only suitable transport mode	Perceived car dependency	Increase	Proposed by authors
Attractiveness/Willingness to use car for transportation	Perceived car dependency	Increase	Proposed by authors
Attractiveness of cycling	Perception of car as only suitable transport mode	Decrease	Proposed by authors based on Weir et al. (2024) and Pokharel et al. (2023)
Attractiveness of public transportation	Perception of car as only suitable transport mode	Decrease	Proposed by authors based on Weir et al. (2024) and Pokharel et al. (2023)
Distance to essential activities/opportunities	Perception of car as only suitable transport mode	Increase	Proposed by authors based on Pokharel et al. (2023)
Perception of car ownership as a choice	Perception of car as only suitable transport mode	Decrease	Based on Zijlstra et al. (2022)
Presence of (physical) disabilities	Perception of car ownership as a choice	Decrease	Proposed by authors
Work-related transport needs	Perception of car ownership as a choice	Decrease	Proposed by authors
Environmental policies and legislations	Public transportation policies	Increase	Based on Weir et al. (2024)
Environmental policies and legislations	Quality of walking and cycling infrastructure	Increase	Based on Weir et al. (2024)
Car use	Road capacity	Decrease	Based on Pokharel et al. (2023)
Investments in car-oriented infrastructure	Road capacity	Increase	Based on Pokharel et al. (2023)
Car-oriented land-use planning	Urban sprawl	Increase	Based on Pokharel et al. (2023)
Investments in car-oriented infrastructure	Urban sprawl	Increase	Based on Pokharel et al. (2023)

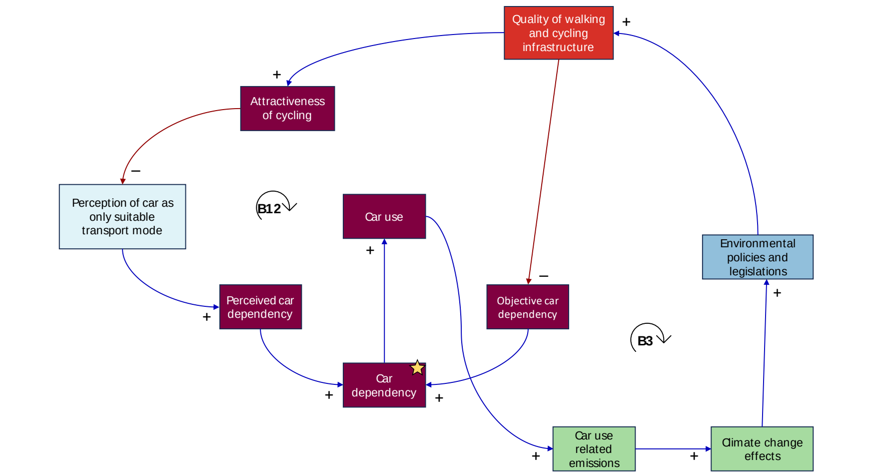
Appendix 2: Feedback loops affecting car dependency identified in CLD

These feedback loops were identified by assessing the CLD and selecting all loops that start and end at car dependency. While this appendix only shows the feedback loops involving car dependency, the same process can be applied for other factors of interest such as car use or car ownership.

Legend

- Star symbol (★): indicates factor of interest (car dependency), which was used as the focal point for identifying the feedback loops.
- ↑: indicates that a change in the previous factor leads to an increase in the current factor
- ↓: indicates that a change in the previous factor leads to a decrease in the current factor
- R indicates a reinforcing feedback loop (i.e., an initial increase in car dependency will be exacerbated by additional increase in car dependency as a result of the interactions between the elements of this feedback loop).
- B indicates a balancing feedback loop (i.e., an initial increase in car dependency will be offset by a decrease in car dependency as a result of the interactions between the elements of this feedback loop).

Feedback loop	Description
	Operation of Loop 1 (**reinforcing**): ↑ Car dependency → ↑ Car use → ↑ Car-oriented mindset and preferences → ↑ Car oriented mobility habits → ↑ Attractiveness/Willingness to use car for transportation → ↑ Perceived car dependency → ↑ Car dependency
	Operation of Loop 2 (**balancing**): ↑ Car dependency → ↑ Car use → ↓ Road capacity → ↑ Congestion → ↓ Attractiveness/Willingness to use car for transportation → ↓ Perceived car dependency → ↓ Car dependency

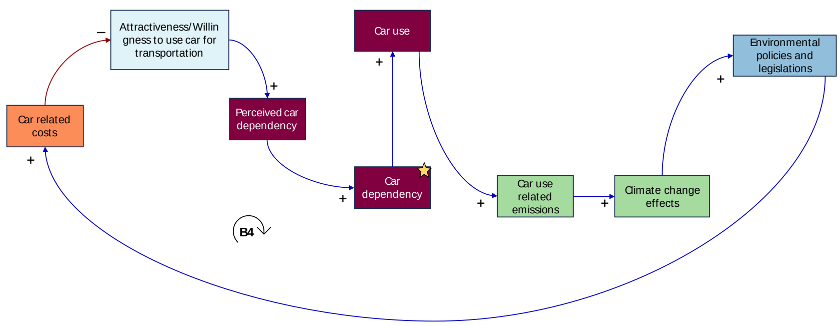


Operation of Loop 3 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Quality of walking and cycling infrastructure → ↓ Objective car dependency → ↓ Car dependency

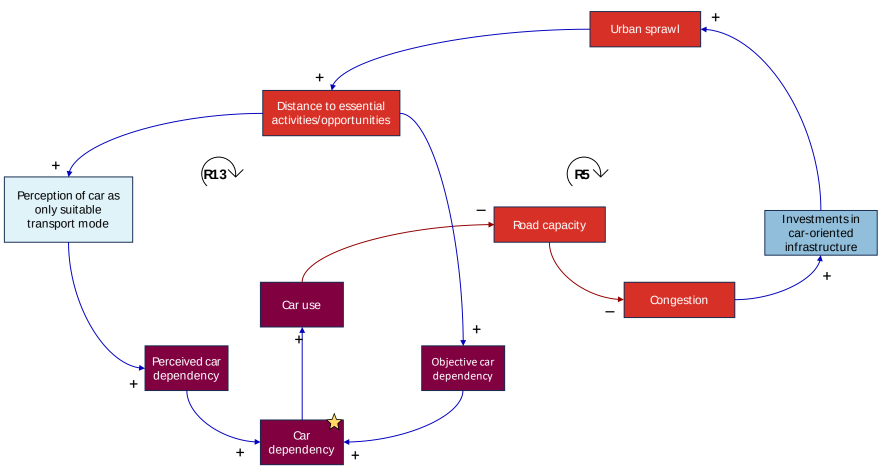
Operation of Loop 12 (**reinforcing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Quality of walking and cycling infrastructure → ↑ Attractiveness of cycling → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency



Operation of Loop 4 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Car related costs → ↓ Attractiveness/Willingness to use car for transportation → ↓ Perceived car dependency → ↓ Car dependency

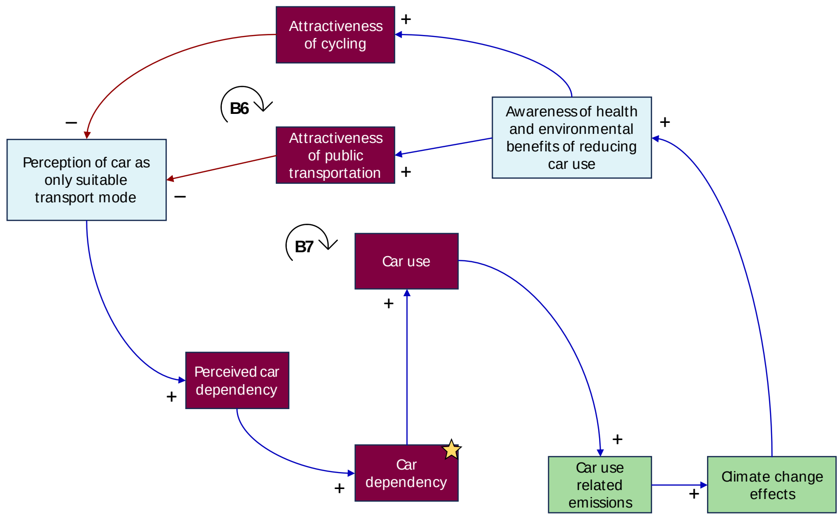


Operation of Loop 5 (**reinforcing**):

↑ Car dependency → ↑ Car use → ↓ Road capacity → ↑ Congestion → ↑ Investments in car-oriented infrastructure → ↑ Urban sprawl → ↑ Distance to essential activities/opportunities → ↑ Objective car dependency → ↑ Car dependency

Operation of Loop 13 (**reinforcing**):

↑ Car dependency → ↑ Car use → ↓ Road capacity → ↑ Congestion → ↑ Investments in car-oriented infrastructure → ↑ Urban sprawl → ↑ Distance to essential activities/opportunities → ↑ Perception of car as only suitable transport mode → ↑ Perceived car dependency → ↑ Car dependency

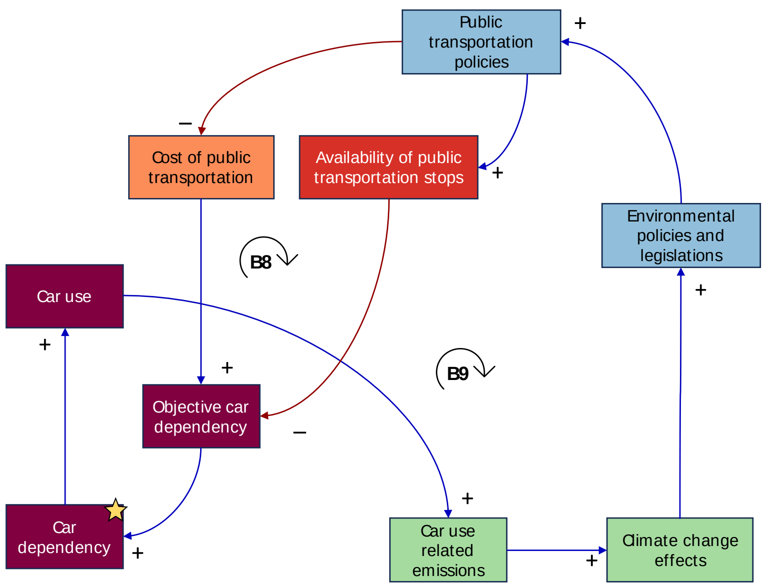


Operation of Loop 6 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Awareness of health and environmental benefits of reducing car use → ↑ Attractiveness of cycling → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency

Operation of Loop 7 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Awareness of health and environmental benefits of reducing car use → ↑ Attractiveness of public transportation → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency

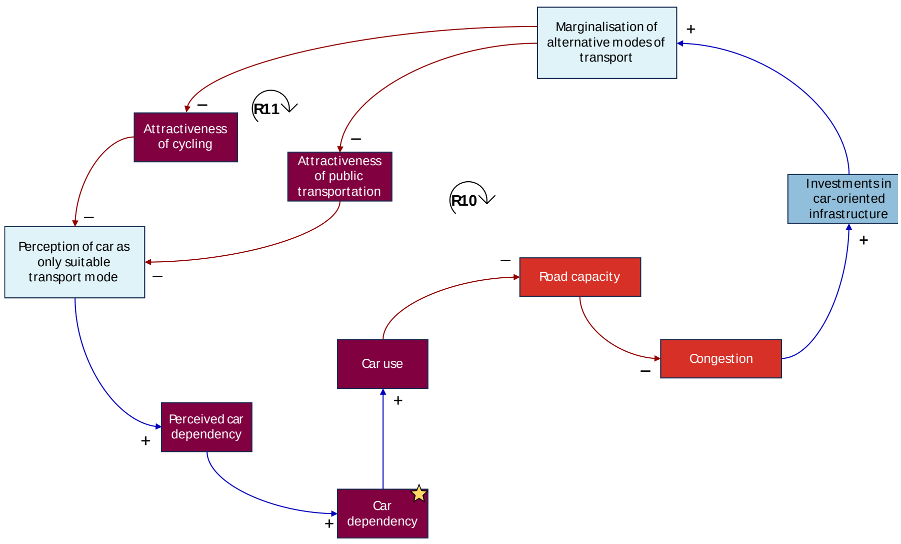


Operation of Loop 8 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Public transportation policies → ↓ Cost of public transportation → ↓ Objective car dependency → ↓ Car dependency

Operation of Loop 9 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Public transportation policies → ↑ Availability of public transportation stops → ↓ Objective car dependency → ↓ Car dependency

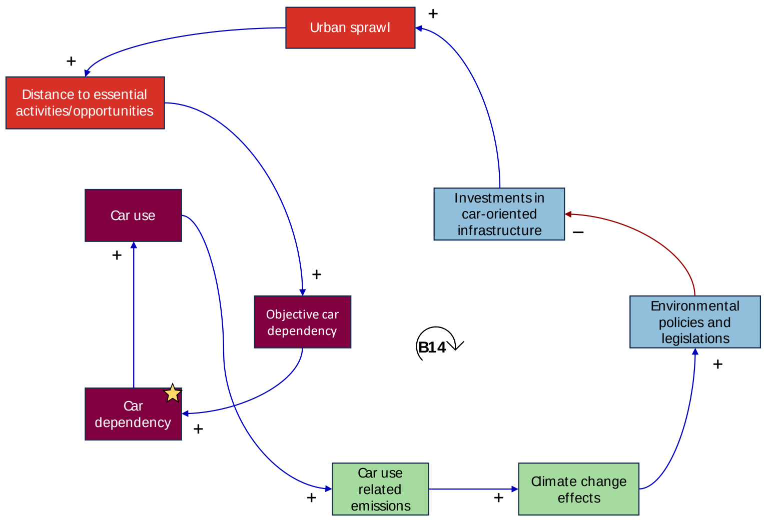


Operation of Loop 10 (**reinforcing**):

↑ Car dependency → ↑ Car use → ↓ Road capacity → ↑ Congestion → ↑ Investments in car-oriented infrastructure → ↑ Marginalisation of alternative modes of transport → ↓ Attractiveness of public transportation → ↑ Perception of car as only suitable transport mode → ↑ Perceived car dependency → ↑ Car dependency

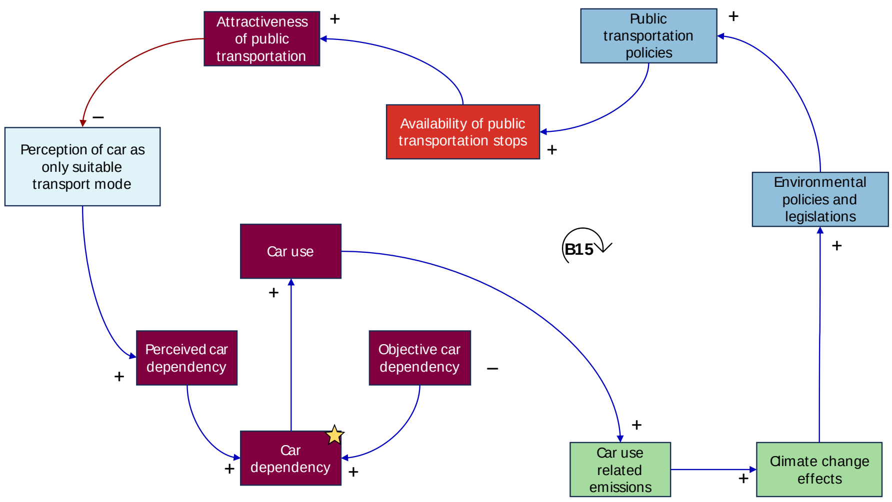
Operation of Loop 11 (**reinforcing**):

↑ Car dependency → ↑ Car use → ↓ Road capacity → ↑ Congestion → ↑ Investments in car-oriented infrastructure → ↑ Marginalisation of alternative modes of transport → ↓ Attractiveness of cycling → ↑ Perception of car as only suitable transport mode → ↑ Perceived car dependency → ↑ Car dependency



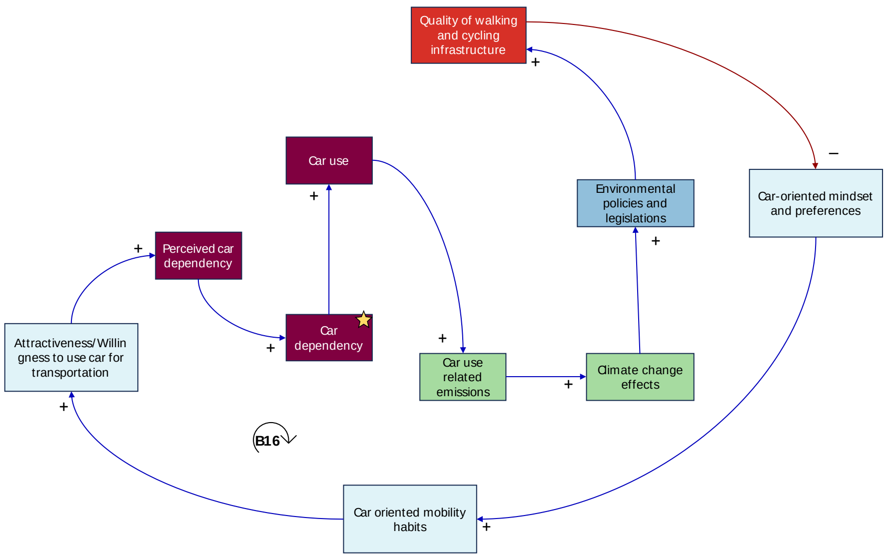
Operation of Loop 14 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↓ Investments in car-oriented infrastructure → ↓ Urban sprawl → ↓ Distance to essential activities/opportunities → ↓ Objective car dependency → ↓ Car dependency



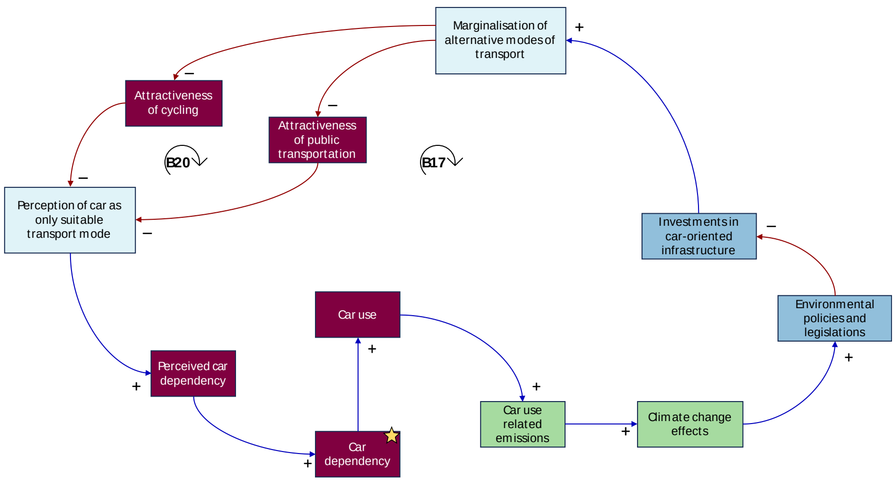
Operation of Loop 15 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Public transportation policies → ↑ Availability of public transportation stops → ↑ Attractiveness of public transportation → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency



Operation of Loop 16 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Quality of walking and cycling infrastructure → ↓ Car-oriented mindset and preferences → ↓ Car oriented mobility habits → ↓ Attractiveness/Willingness to use car for transportation → ↓ Perceived car dependency → ↓ Car dependency

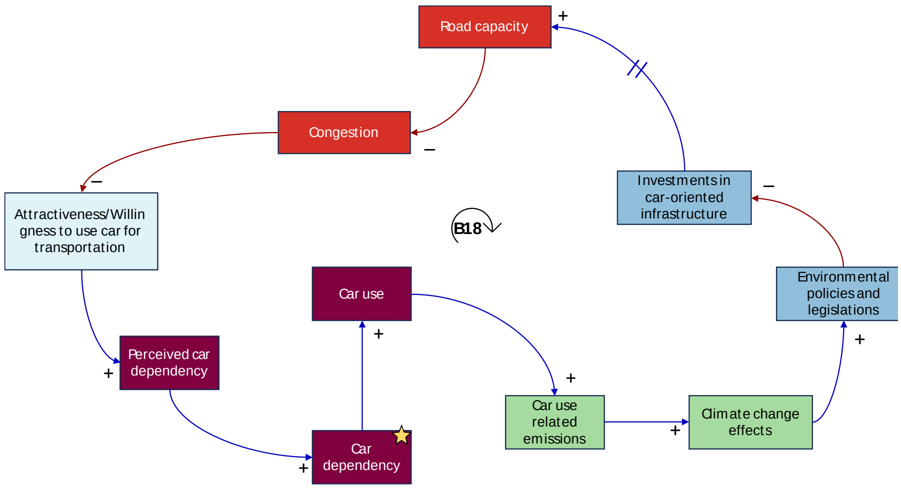


Operation of Loop 17 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↓ Investments in car-oriented infrastructure → ↓ Marginalisation of alternative modes of transport → ↑ Attractiveness of public transportation → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency

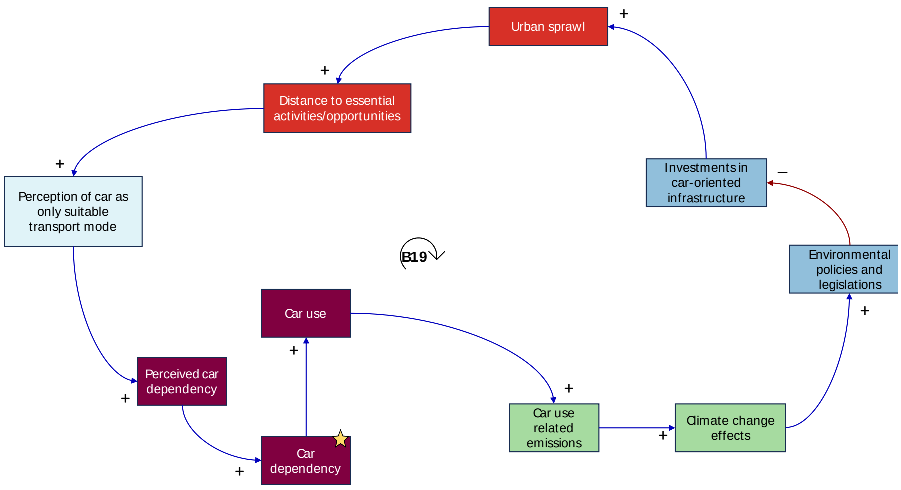
Operation of Loop 20 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↓ Investments in car-oriented infrastructure → ↓ Marginalisation of alternative modes of transport → ↑ Attractiveness of cycling → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency



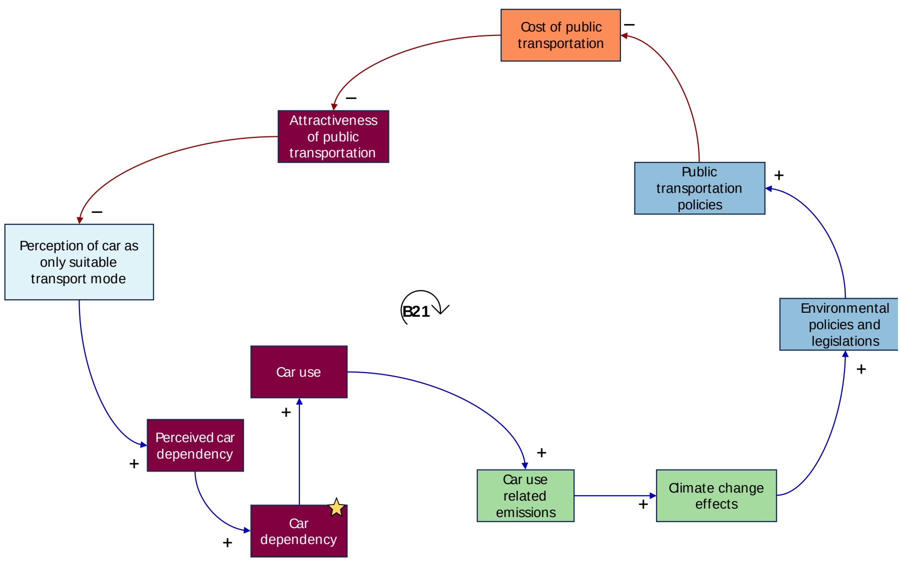
Operation of Loop 18 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↓ Investments in car-oriented infrastructure → ↓ Road capacity → ↑ Congestion → ↓ Attractiveness/Willingness to use car for transportation → ↓ Perceived car dependency → ↓ Car dependency



Operation of Loop 19 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↓ Investments in car-oriented infrastructure → ↓ Urban sprawl → ↓ Distance to essential activities/opportunities → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency



Operation of Loop 21 (**balancing**):

↑ Car dependency → ↑ Car use → ↑ Car use related emissions → ↑ Climate change effects → ↑ Environmental policies and legislations → ↑ Public transportation policies → ↓ Cost of public transportation → ↓ Attractiveness of public transportation → ↓ Perception of car as only suitable transport mode → ↓ Perceived car dependency → ↓ Car dependency

Appendix 3: Effect of AVs scenarios on car dependency, car use and car ownership using the CLD

The consolidated expected effects of the different scenarios on the three factors of interest – car dependency, car use and car ownership – are determined by identifying all paths from the expected direct impacts of the scenarios (e.g. change in attractiveness of the car) to these factors of interest. The paths are all coded with a scenario (S1/S2/S3), a specific direct impact factor at the start of the path (A/B/C/etc.), one of the three factors of interest at the end of the path (1/2/3), and a specific path through the CLD between the start and end factors (.1/.2/.3/etc.). This results in codes such as S1B3.2.

Consolidated expect effect of AVs on car dependency (Scenario 1: Private AVs)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car dependency	(S1A1.1/ S1B1.1/ S1B1.2/ S1B1.3/S1B1.4/ S1B1.5/ S1C1.1/ S1C1.2): ((↑) Increase / (↓) Decrease / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase)	S1A1.1: (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency S1B1.1: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) Perceived car dependency → (↓) Car dependency S1B1.2: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S1B1.3: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S1B1.4: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency S1B1.5: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S1C1.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency

S1C1.2: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency

Consolidated expect effect of AVs on car ownership (Scenario 1: Private AVs)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
(Likelihood of) car ownership	(S1A2.1/ S1B2.1/ S1B2.2/ S1B2.3/ S1B2.4/ S1C2.1): ((↑) Increase / (↓) Decrease / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase)	S1A2.1: (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership S1B2.1: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) car ownership S1B2.2: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) car ownership S1B2.3: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) car ownership S1B2.4: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership S1C2.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership

Consolidated expect effect of AVs on car use (Scenario 1: Private AVs)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S1A3.1 / S1B3.1/ S1B3.2/ S1B3.3/ S1C3.1): ((↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↓) Decrease)	S1A3.1: (↑) car ownership → (↑) Car use S1B3.1: (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership → (↑) Car use S1B3.2: (↑) Attractiveness/Willingness to use car for transportation → (↑) Car use S1B3.3: (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S1C3.1: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) Car use
Car use	(S1C3.10/ S1C3.2/ S1C3.3/ S1C3.4/ S1C3.5): ((↑) Increase/(↓) Decrease/(↓) Decrease/(↑) Increase/(↑) Increase)	S1C3.10: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S1C3.2: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) car ownership → (↓) Car use S1C3.3: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S1C3.4: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S1C3.5: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use

Consolidated expect effect of AVs on car use (Scenario 1: Private AVs) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S1C3.6/ S1C3.7/ S1C3.8/ S1C3.9/ S1D3.1/ S1D3.2/ S1D3.3): ((↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase)	S1C3.6: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S1C3.7: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S1C3.8: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency → (↑) Car use S1C3.9: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S1D3.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S1D3.2: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency → (↑) Car use S1D3.3: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use

Consolidated expect effect of AVs on car dependency (Scenario 2: Robo-taxis)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car dependency	(S2A1.1 / S2B1.1 / S2B1.10 / S2B1.2 / S2B1.3 / S2B1.4 / S2B1.5 / S2B1.6): ((↑) Increase / (↓) Decrease / (↓) Decrease / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase)	S2A1.1: (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency S2B1.1: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) Perceived car dependency → (↓) Car dependency S2B1.10: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S2B1.2: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S2B1.3: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S2B1.4: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency S2B1.5 : (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S2B1.6: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency

Consolidated expect effect of AVs on car dependency (Scenario 2: Robo-taxis) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car dependency	(S2B1.7 / S2B1.8 / S2B1.9 / S2C1.1 / S2C1.2 / S2D1.1 / S2E1.1 / S2F1.1) : ((↓) Decrease / (↓) Decrease / (↓) Decrease / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase)	S2B1.7: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S2B1.8: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S2B1.9: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Objective car dependency → (↓) Car dependency S2C1.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency S2C1.2 : (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S2D1.1 : (↓) Car related costs → (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency S2E1.1 : (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S2F1.1 : (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency

Consolidated expect effect of AVs on car ownership (Scenario 2: Robo-taxis)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
(Likelihood of) car ownership	(S2A2.1 / S2B2.1 / S2B2.2 / S2B2.3 / S2B2.4 / S2B2.5 / S2B2.6) : ((↑) Increase / (↓) Decrease / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase / (↓) Decrease)	S2A2.1: (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership S2B2.1: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) car ownership S2B2.2: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) car ownership S2B2.3: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) car ownership S2B2.4: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership S2B2.5: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership S2B2.6: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) car ownership

Consolidated expect effect of AVs on car ownership (Scenario 2: Robo-taxis) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
(Likelihood of) car ownership	(S2B2.7 / S2B2.8 / S2C2.1 / S2D2.1 / S2D2.2 / S2E2.1 / S2F2.1) : ((↓) Decrease / (↓) Decrease / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase / (↑) Increase)	S2B2.7: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership S2B2.8: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) car ownership S2C2.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership S2D2.1: (↓) Car related costs → (↑) car ownership S2D2.2: (↓) Car related costs → (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership S2E2.1 : (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) car ownership S2F2.1 : (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) car ownership

Consolidated expect effect of AVs on car use (Scenario 2: Robo-taxis)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S2A3.1/S2B3.1/S2B3.2/S2B3.3/S2C3.1/ S2C3.10/S2C3.11/S2C3.12/S2C3.13/S2C3.14): ((↓) Decrease/(↑) Increase/(↑) Increase/(↑) Increase/(↓) Decrease/(↑) Increase/(↑) Increase/(↑) Increase/(↓) Decrease/(↓) Decrease)	S2A3.1: (↓) car ownership → (↓) Car use S2B3.1: (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership → (↑) Car use S2B3.2: (↑) Attractiveness/Willingness to use car for transportation → (↑) Car use S2B3.3: (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S2C3.1: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) Car use S2C3.10: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership → (↑) Car use S2C3.11: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) Car use S2C3.12: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S2C3.13: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S2C3.14: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use

Consolidated expect effect of AVs on car use (Scenario 2: Robo-taxis) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S2C3.15/S2C3.16/S2C3.17/S2C3.18/S2C3.19/ S2C3.2/S2C3.3/S2C3.4/S2C3.5): ((↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↑) Increase/(↑) Increase)	S2C3.15: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S2C3.16: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S2C3.17: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Objective car dependency → (↓) Car dependency → (↓) Car use S2C3.18: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S2C3.19: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S2C3.2: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) car ownership → (↓) Car use S2C3.3: (↑) Congestion → (↓) Attractiveness/Willingness to use car for transportation → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S2C3.4: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S2C3.5: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use

Consolidated expect effect of AVs on car use (Scenario 2: Robo-taxis) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S2C3.6/S2C3.7/S2C3.8/S2C3.9/S2D3.1/ S2D3.2/S2D3.3/S2E3.1 /S2F3.1): ((↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase)	S2C3.6: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S2C3.7: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Marginalisation of alternative modes of transport → (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S2C3.8: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency → (↑) Car use S2C3.9: (↑) Congestion → (↑) Investments in car-oriented infrastructure → (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S2D3.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S2D3.2: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency → (↑) Car use S2D3.3: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S2E3.1 : (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S2E3.2 : (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use

Consolidated expect effect of AVs on car use (Scenario 2: Robo-taxis) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S2F3.1/S2F3.2/S2G3.1/S2G3.2/S2G3.3/ S2G3.4): (↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase/(↑) Increase	S2F3.1 : (↓) Attractiveness of cycling → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S2F3.2: (↓) Attractiveness of public transportation → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S2G3.1: (↓) Car related costs → (↑) car ownership → (↑) Car use S2G3.2: (↓) Car related costs → (↑) Attractiveness/Willingness to use car for transportation → (↑) Car use S2G3.3: (↓) Car related costs → (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership → (↑) Car use S2G3.4: (↓) Car related costs → (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use

Consolidated expect effect of AVs on car dependency (Scenario 3: Robo-buses)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car dependency	(S3A1.1 / S3A1.2 / S3A1.3 / S3A1.4 / S3A1.5 / S3B1.1 / S3B1.2 / S3C1.1 / S3C1.2 / S3D1.1 / S3E1.1) : ((↑) Increase / (↓) Decrease / (↓) Decrease / (↓) Decrease / (↓) Decrease / (↑) Increase / (↑) Increase / (↓) Decrease / (↓) Decrease / (↓) Decrease / (↓) Decrease)	S3A1.1: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency S3A1.2: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S3A1.3: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S3A1.4: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Objective car dependency → (↓) Car dependency S3A1.5: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S3B1.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency S3B1.2: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency S3C1.1: (↓) Cost of public transportation → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S3C1.2: (↓) Cost of public transportation → (↓) Objective car dependency → (↓) Car dependency S3D1.1: (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency S3E1.1: (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency

Consolidated expect effect of AVs on car ownership (Scenario 3: Robo-buses)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
(Likelihood of) car ownership	(S3A2.1 / S3A2.2 / S3A2.3 / S3A2.4 / S3B2.1 / S3C2.1 / S3D2.1 / S3E2.1) : ((↑) Increase / (↓) Decrease / (↓) Decrease / (↓) Decrease / (↑) Increase / (↓) Decrease / (↓) Decrease / (↓) Decrease)	S3A2.1: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership S3A2.2: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) car ownership S3A2.3: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership S3A2.4: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) car ownership S3B2.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership S3C2.1: (↓) Cost of public transportation → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership S3D2.1: (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) car ownership S3E2.1: (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership

Consolidated expect effect of AVs on car use (Scenario 3: Robo-buses)

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S3A3.1/S3B3.1/S3B3.10/S3B3.2/S3B3.3/ S3B3.4/S3B3.5/S3B3.6/S3B3.7/S3B3.8) : ((↓) Decrease/(↑) Increase/(↓) Decrease/(↑) Increase/(↑) Increase/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease)	S3A3.1: (↓) car ownership → (↓) Car use S3B3.1: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) car ownership → (↑) Car use S3B3.10: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S3B3.2: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) Car use S3B3.3: (↓) Congestion → (↑) Attractiveness/Willingness to use car for transportation → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S3B3.4: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S3B3.5: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S3B3.6: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S3B3.7: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Marginalisation of alternative modes of transport → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S3B3.8: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Objective car dependency → (↓) Car dependency → (↓) Car use

Consolidated expect effect of AVs on car use (Scenario 3: Robo-buses) – continued.

Factor of interest	Consolidated expect effect on factor of interest	Loop paths (from affected factors in Tables 2,3,4 to factor of interest)
Car use	(S3B3.9/S3C3.1/S3C3.2/S3C3.3/S3D3.1/S3D3.2/S3D3.3/S3E3.1/S3E3.2/S3F3.1/S3F3.2): ((↓) Decrease/(↑) Increase/(↑) Increase/(↑) Increase/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease/(↓) Decrease)	S3B3.9: (↓) Congestion → (↓) Investments in car-oriented infrastructure → (↓) Urban sprawl → (↓) Distance to essential activities/opportunities → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S3C3.1: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Objective car dependency → (↑) Car dependency → (↑) Car use S3C3.2: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) car ownership → (↑) Car use S3C3.3: (↑) Urban sprawl → (↑) Distance to essential activities/opportunities → (↑) Perception of car as only suitable transport mode → (↑) Perceived car dependency → (↑) Car dependency → (↑) Car use S3D3.1: (↓) Cost of public transportation → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S3D3.2: (↓) Cost of public transportation → (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S3D3.3: (↓) Cost of public transportation → (↓) Objective car dependency → (↓) Car dependency → (↓) Car use S3E3.1: (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S3E3.2: (↑) Attractiveness of cycling → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use S3F3.1: (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) car ownership → (↓) Car use S3F3.2: (↑) Attractiveness of public transportation → (↓) Perception of car as only suitable transport mode → (↓) Perceived car dependency → (↓) Car dependency → (↓) Car use