The medium-term impacts of cooperative, connected, and automated mobility on passenger transport

Deliverable D6.3 – WP6 – PU

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List of abbreviations

ACC	Adaptive Cruise Control
AIT	Austrian Institute of Technology
API	Application Programming Interface
AV	Automated Vehicle
CACC	Cooperative Adaptive Cruise Control
CATS	Connected And Automated Transport Systems
CAV	Connected And Autonomous Vehicle
CCAM	Cooperative, Connected and Automated Mobility
CC	City Centre
C-ITS	Cooperative Intelligent Transport Systems
CV	Connected Vehicle
DRS	Dynamic Ride Sharing
ERTRAC	European Road Transport Research Advisory Council
EU	European Union
EV	Electric Vehicle
GLOSA	Green Light Optimal Speed Advisory
HDV	Human Driven Vehicles
HGV	Heavy Goods Vehicle
HOV	High Occupancy Vehicle
HOT	High Occupancy Toll
IC	Inner City
IP	Intra Peripheral
Ldm	Longest distance mode
LGV	Large Goods Vehicles
MPR	Market Penetration Rate
mUoM	Marginal Utility of Money
NHTSA	National Highway Traffic Safety Administration
NRC	National Research Council
PCU	Passenger Car Unit
PST	Policy Support Tool
PT	Public Transport
RUP	Road Use Pricing
XP	Extra Peripheral
SAE	Society of Automotive Engineers
SAV	Shared Autonomous Vehicle
SD	System Dynamics

SRG	Stakeholder Reference Group
SUC	Sub-use Case
TTC	Time To Collision
UC	Use Case
V2I	Vehicle To Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VHT	Vehicle Hours Travelled
VKT	Vehicle Kilometres Travelled
VMT	Vehicle Miles Travelled
VTTS	Value of Travel Time Saved
VRPPDTW	Vehicle Routing Problem with Pickup and Delivery with Time Window
WTS	Willingness to Share

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Executive summary

The aim of the LEVITATE project is to prepare a new impact assessment framework to enable policymakers to manage the introduction of connected and automated transport systems, maximise the benefits and utilise the technologies to achieve societal objectives. As part of this work the LEVITATE project seeks to forecast societal level impacts of cooperative, connected, and automated mobility (CCAM). These include impacts on mobility, safety, environment, economy, and society.

This report presents a wide range of medium-term or systemic impacts of CCAM and various policy interventions for managing passenger car transport. The medium-term impacts analysed include congestion, amount of travel, model split using public transport, model split using active travel, shared mobility rate, vehicle utilization rate and vehicle occupancy. Based on discussions with city officials and industry professionals, a list of key interventions, termed sub-use cases (SUC), were selected to be tested through different applicable methods. These include road use pricing, provision of dedicated lanes on urban highways, parking price policies, parking space regulations, automated ride sharing, and green light optimal speed advisory (GLOSA). The methodologies for analysing the impacts of the studied interventions were selected based on their feasibility and adequacy in examining the system level or medium-term impacts. They included mesoscopic simulation, microscopic simulation, system dynamics, and Delphi method. The deployment of CAVs was tested from 0 to 100% with 20% increments under all SUCs. The behaviours of CAVs were defined based on an extensive literature review performed as part of the LEVITATE project. Two types of CAVs were included in the analysis, 1st Generation CAVs and second Generation CAVs, where 2nd generation CAVs were assumed to have improved driving characteristics and enhanced cognitive capabilities, which will lead to shorter time gaps as compared to 1st generation CAVs and human-driven vehicles.

Overall, the results from different tested policies and methods provided insightful findings with respect to various key performance indicators. Variations in results from different methods and different networks were observed. In general, increasing automation without any other policy intervention (i.e., baseline scenario) was estimated to progressively increase the amount of travel, shared mobility rate, and vehicle utilisation rate. The microsimulation results have shown potentially adverse impacts on congestion during the transition phases or mixed fleet scenarios.

With the provision of dedicated lanes on urban highways, the microsimulation results showed improved traffic performance (reduced delays) under innermost lane placement on the test network. The parking price policies can potentially create additional delays in the system, reduce the distance travelled, and impact the overall network performance. 'Balanced' and 'heavy return to origin and park outside' strategies were found to have better performance than 'drive around' strategy. With regard to parking space regulations, replacing on-street parking with driving lane, cycle lane and public spaces can result in better traffic performance compared to removing half of the on-street parking spaces and replacing them with pick-up/drop-off spaces. Automated ride sharing services were found to have a negative impact on the network performance due to the increased number of trips and the empty vehicle kilometres travelled (VKT) caused by making repositioning trips to reach new travellers. Implementation of a GLOSA system on multiple intersections along a corridor can provide added benefits in terms of reducing delays and improving traffic flow.

With respect to changes in modal split, the findings showed a consistent reduction in public transport modal share with increasing automated vehicles (AV) in the system. Road use pricing policies were found to potentially increase modal shift to public transport. On the other hand, the intervention of replacing on-street parking with driving lanes could potentially reduce the share of public transport users due to increased road capacity encouraging more vehicles on the roads. Active travel was found to be negatively impacted with increasing automation as well as with certain parking space and price policies such as replacing on-street parking with driving lanes and policy on parking price generating 'balanced' parking behaviours, respectively. Automated ride sharing services were also found to negatively impact active travel.

Delphi study results showed an increase in vehicle utilisation rate and shared mobility with the introduction of automated vehicles, whereas vehicle occupancy was not predicted to be significantly impacted with just automation. However, experts predicted an increase in vehicle occupancy, vehicle utilisation rate, and shared mobility with the inclusion of dedicated lanes, parking price policies, as well as with the implementation of GLOSA system. Increases in shared mobility was also predicted by the experts due to replacing on-street parking with space for public use, with driving lanes or with pick-up/drop-off parking space. With respect to vehicle utilisation rates, the experts expected a strong impact due to parking price policies where the 'return to origin' strategy was indicated to have the increased impact as compared to the 'drive around' and 'park outside' and 'park inside' scenarios. The Delphi study results also indicated that automated ride sharing services can significantly impact vehicle occupancy as compared to the baseline scenario. Replacing on-street parking with spaces for public use or pick-up/drop-off spaces were considered to increase vehicle occupancy with increasing automation. 'Park inside' policy was also indicated to increase vehicle occupancy in the long term.

Overall, the results provide important messages for city governments to manage potential consequences due to the introduction of CAVs in the transport system. One method may not fit well under all impacts and therefore, combinations of methods need to be evaluated for the most optimal policies. Through the findings, there are opportunities for cities to develop strategies for mitigating the potentially adverse impacts.

1 Introduction

1.1 LEVITATE

Societal **Lev**el **I**mpacts of Connec**t**ed and **A**utoma**t**ed Vehicl**e**s (LEVITATE) (LEVITATE) is a European Commission supported Horizon 2020 project with the objective to prepare a new impact assessment framework to enable policymakers to manage the introduction of connected and automated transport systems, maximise the benefits and utilise the technologies to achieve societal objectives.

Cooperative, connected, and automated mobility (CCAM) are expected to be introduced in increasing numbers over the next decade. Automated vehicles have attracted the public imagination and there are high expectations in terms of safety, mobility, environment, and economic growth. With such systems not yet in widespread use, there is a lack of data and knowledge about impacts.

The potentially disruptive nature of highly automated vehicles makes it very difficult to determine future impacts from historic patterns. Estimates of future impacts of automated and connected mobility systems may be based on forecasting approaches, yet there is no agreement over the methodologies nor the baselines to be used. The need to measure the impact of existing systems as well as forecast the impact of future systems represents a major challenge. The dimensions for assessment themselves are very wide, including safety, mobility, and environment. The multiple sub-divisions of these add to the complexity of future mobility forecasts.

Specifically LEVITATE has four key objectives:

1. To establish **a multi-disciplinary methodology** to assess the short, medium, and long-term impacts of CCAM on mobility, safety, environment, society, and other impact areas. Several quantitative indicators will be identified for each impact type.

2. To develop a range of **forecasting and backcasting** scenarios and baseline conditions relating to the deployment of one or more mobility technologies that will be used as the basis of impact assessments and forecasts. These will cover three primary use cases – automated urban shuttle, passenger cars and freight services.

3. To apply the methods and forecast the impact of CCAM over the short, medium, and long term for a range of use cases, operational design domains and environments and an extensive range of mobility, environmental, safety, economic and societal indicators. A series of case studies will be conducted to validate the methodologies and to demonstrate the system.

4. To incorporate the established methods within a **new web-based policy support tool** to enable city and other authorities to forecast impacts of CCAM on urban areas. The methods developed within LEVITATE will be available within a toolbox allowing the impact of measures to be assessed individually. A Decision Support System will enable users to apply backcasting methods to identify the sequences of CCAM measures that will result in their desired policy objectives.

1.2 Work Package 6 and Deliverable 6.3 within LEVITATE

Work Package 6 (WP6) considers the specific case of passenger cars which are used across the transport system and forecasting of impacts involved the use on urban, rural and highway infrastructure.

Forecasting in WP6 is based on the methodology developed in WP3 and the scenarios developed in WP4 to identify and test specific scenarios regarding the impacts of CATS on passenger cars. Findings will complement those of WP5 (Urban transport) and WP7 (Freight) and feed into the developing of the LEVITATE Policy Support Tool (PST) in WP8. More specifically, the purpose of Work Package 6 (WP6) is:

- To identify how each area of impact (safety, mobility, environment, economy, and society) will be affected by the transition of passenger cars into Connected and automated vehicles with focus on the transition towards higher levels of automation. Impacts on traffic will be considered cross cutting the other dimensions,

- To assess the short, **medium,** and long-term impacts, benefits, and costs of cooperative and automated driving systems for passenger cars,

- To test interactions of the examined impacts in passenger cars, and

- To prioritise considerations for a public policy support tool to help authority decisions.

The purpose of Deliverable 6.3 is to present the **medium-term impacts** of cooperative, connected, and automated driving in passenger cars. The exact impacts of interest and how to measure these have been previously defined in WP3 and WP4. The medium-term impacts are considered to be those measured indirectly from direct impacts and specific nature of medium-term context has been defined in D6.1 (Boghani et al., 2019). The main methodological approaches to forecast the medium-term impacts are microscopic traffic simulation modelling, mesoscopic mobility simulation modelling, system dynamics, Delphi, or classical statistical models. The simulation modelling approaches are used estimate the road network-level impacts of the integration of different impacts for different transport types, modes, and actors. Within deliverable 6.3, focus is placed on medium-term or system level impacts including congestion, amount of travel, model split using public transport, model split using active travel, shared mobility rate, vehicle utilization rate and vehicle occupancy.

Table 1.1 presents an overview of the list of impacts considered in the PST for WP6, along with a short description and the unit of measurement. Highlighted are those handled in this deliverable.

Table 1.1: Overview of the impacts in WP6. Highlighted are the medium-term impacts for this deliverable.

Impact	Description	Method
Short term impacts / direct impacts		
Travel time	Average duration of a 5Km trip inside the city centre	Mesoscopic simulation/ Microscopic simulation/Delphi
Vehicle operating cost	Direct outlays for operating a vehicle per kilometre of travel	Delphi
Access to travel	The opportunity of taking a trip whenever and wherever wanted (10 points Likert scale)	Delphi
Medium term impacts / systemic impacts		
Congestion	Average delays to traffic (seconds per vehicle-kilometre) as a result of high traffic volume	Microscopic simulation
Amount of travel	Person kilometres of travel per year in an area	Mesoscopic simulation/Microscopic simulation/Delphi
Modal split using public transport	% of trip distance made using public transportation	Mesoscopic simulation/ System dynamics/Delphi
Modal split using active travel	% of trip distance made using active transportation (walking, cycling)	Mesoscopic simulation/ System dynamics/Delphi
Shared mobility rate	% of trips made sharing a vehicle with others	Delphi
Vehicle utilisation rate	% of time a vehicle is in motion (not parked)	Delphi
Vehicle occupancy	average % of seats in use	Delphi
Long term impacts / wider impacts		
Road safety	Number of traffic conflicts per vehicle-kilometre driven (temp. until crash relation is defined).	Road safety method
Parking space	Required parking space in the city centre per person (m2/person)	System dynamics/Delphi
Energy efficiency	Average rate (over the vehicle fleet) at which propulsion energy is converted to movement	Delphi
NO_x due to vehicles	Concentration of NO_x pollutants as grams per vehicle-kilometre (due to road transport only)	Microscopic simulation
CO_2 due to vehicles	Concentration of CO_2 pollutants as grams per vehicle-kilometre (due to road transport only)	Microscopic simulation
PM_{10} due to vehicles	Concentration of PM_{10} pollutants as grams per vehicle-kilometre (due to road transport only)	Microscopic simulation
Public health	Subjective rating of public health state, related to transport (10 points Likert scale)	Delphi

Accessibility in transport	The degree to which transport services are used by socially disadvantaged and vulnerable groups including people with disabilities (10 points Likert scale)	Delphi
Commuting distances	Average length of trips to and from work (added together)	System dynamics

2 Sub-use cases

Sub-use case (SUC) in this deliverable refers to subcategory (mostly related to a policy intervention) under passenger car use-case developed to study the quantifiable impacts of CCAM on passenger transport. From the stakeholder reference group (SRG) workshop, detailed in D 6.1 (Boghani et al., 2019), consultation was obtained from the experts from city administrations and industry on the generation and prioritization of the sub-use cases. Within LEVITATE, this list has been prioritized and refined within subsequent tasks in the project to inform the interventions and scenarios related to passenger transport. In turn, these SUCs will be included in the LEVITATE Policy Support Tool (PST).

The prioritisation of the sub-use cases mainly took these three input directions into account:

- Scientific literature: Indicating the scientific knowledge and the available assessment methodologies for the sub-use cases. However, this might not be directly linked to their importance / relevance for practice.

- Roadmaps: Indicating the relevance of sub-use cases from the industrial/ political point of view, independent of available scientific methodologies.

- SRG Workshop: Containing first-hand feedback for the sub-use cases but might only reflect the opinions of organisations and people who participated.

- Results of the backcasting city dialogues conducted in LEVITATE WP4 for Vienna, Greater Manchester, and Amsterdam (Zach, Sawas, Boghani, & de Zwart, 2019; Papazikou et al., 2020).

Considering the suggestions from SRG and existing knowledge through literature, six key sub-use cases have been defined within WP6 as follows:

1) Road use pricing (RUP):
2) Provision of dedicated lanes for AVs on urban highways
3) Parking price policies
4) Parking space regulation
5) Automated ride sharing, and
6) Green Light Optimal Speed Advisory (GLOSA)

2.1 Road use pricing (RUP)

The term road-use pricing refers to charges for the use of infrastructure, including distance and time-based fees, road tolls and various charges with the scope to discourage the access or long-stay of vehicles within an area.

Within LEVITATE the two different price charging schemes are considered as defined above for all passenger vehicles for a commercial mixed traffic zone. Here, "dynamic toll" is to be understood as a toll with dependency on occupancy (empty km or car sharing), time (system entry time), and space (road class or/and zone), while the unit pricing for those parameters could be fixed per respective unit (e.g., peak-hours/off-peak hours, km, persons). Differently, the "static toll" refers to a fixed fee or tax paid by users to enter a tolling area.

The road use pricing has raised significant interest and attention during the dialogue with cities and stakeholders, who made it apparent that they would like to investigate both pricing models/options in order to adopt the optimum policy according to their priorities and their city vision.

In the initial list of interventions to explore, there was also a differentiation in tolls between the human driven and fully automated vehicles. However, after the dialogue with the cities' representatives, it became clear that their *vision focuses on the reduction of any private motorised vehicle in their city centre*, rendering the toll variance meaningless.

2.1.1 Literature review

Existing urban systems

Existing road-use pricing systems concern a specific highway or highway network, or a well-defined city centre area. The major city systems in operation include London, Singapore, Stockholm and Milan. The charge can be modified during peak-hours or increased congestion. The performance of each system depends heavily on its specificities. Table 2.1 summarises the characteristics of the road-charging schemes in these four cities.

Table 2.1: Characteristics of existing road-use pricing schemes (IEA/OECD, 2009)

Town	Name	Date implemented	Scheme type	Area (km²)	Operating hours	Price	Enforcement system
Singapore	Electronic road pricing	1975	Cordon ring (in)	7	Mo-Sa 7.00 - 22.00	Gantry / time dependent EUR 0 to 1.5	Radiofrequencies + cameras
London	Congestion charge	2003	Cordon ring (in)	40	Mo-Fr 7.00-18.30	Flat rate, GBP 8/day	CCTV cameras
Stockholm	Congestion tax	2006 (became permanent in 2007)	Cordon ring (in and out)	35	Mo-Fr 6.30-18.30	EUR 1 to 2/crossing depending on time of day	Laser + cameras
Milan	Ecopass	2008 (temporary through end of 2009; extension possible)	Cordon ring (in)	8	Mo-Fr 7.30-19.30	EUR 2 to 10/day	Digital cameras

In terms of the impact of such policies, they decrease congestion as they affect the amount of traffic and also, the amount of vehicle utilisation. Other beneficial impacts concern emissions drop, CO_2 emissions reductions and safety (Transport for London, 2007; Eliasson, Hultkrantz, Nerhagen & Rosqvistk, 2009). It is generally supported that the implementation of cordon schemes of congestion pricing in large urban areas could have a beneficial and wider impact on society (IEA/OECD, 2009).

2.1.2 Political sensitivity of the sub-use case and implications

Road-use or congestion pricing schemes have faced opposition and protests. It has been criticised as not equitable, with adverse effects in the economy of neighbourhoods and on retail businesses, or as another tax. Nevertheless, under appropriate supporting conditions, economics evaluations mostly agree on the viability of the intervention to reduce congestion and control traffic in the city centre (Kopp & Prud'Homme, 2010; Anas & Lindsey, 2011; Croci, 2016).

Within the LEVITATE project, outcomes from the mesoscopic simulation on this intervention are disseminated via the present report and the deliverable D6.2 (Haouari et al. 2021) for short-term and medium-term impact assessment. Emphasis will be given wherever appropriate within the deliverables or case study documents. These are only case studies to see the effects of road use pricing intervention in those cities and not necessarily their intention or decision to implement such intervention.

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In the initial list of interventions to explore, there was also a differentiation in tolls between the human-driven and fully automated vehicles. However, after the dialogue with the cities' representatives, it became clear that their vision focuses on reducing any private motorised vehicle in their city centre, rendering the toll variance meaningless.

2.1.3 Implementation

The method identified as most applicable to derive conclusions on changing mobility behaviour that is caused by variation of mobility pricing schemes, is an agent based macroscopic mobility simulation of activity chains with an underlying calibrated choice model. This method has been applied previously to investigate RUP measures at several implementation sites:

- Meyer de Freitas, Schuemperlin, and Balać. (2016): Different toll levels in Zurich were simulated until a reduction of 20% vehicle kilometres travelled was reached.
- Kaddoura and Kickhöfer (2014): Application of road pricing to the MATSim Sioux Fall scenario.
- Simoni Kockelman, Gurumurthy, and Bischoff (2019): The authors applied road pricing strategies in combination with AV vehicles.

Further assumptions made to investigate the SUC's scenarios for tolling imposed on the inner-city region of the overall model area, are detailed in section 3.2. These assumptions allow for consideration of both static pricing upon toll-area entry as well as dynamic pricing depending on the travelled distance within the toll-area.

2.2 Provision of dedicated lanes on urban highways

According to Connected Automated Driving Roadmap from ERTRAC (2019), Dedicated AV Lane is a lane where vehicle(s) with specific automation level(s) are allowed but the area is not confined (it would be segregated in that case). It is envisaged that where a dedicated public transport lane is in operation, the dedicated AV lane would be integrated with the dedicated public transport lane, allowing both types of vehicles.

The discussions within the stakeholder reference group (SRG) meeting and findings from recent literature suggest that certain policies and regulations can directly influence the adoption of CAVs, such as road use pricing, parking fee, dedicated lanes, cost of owning and operating a car and many more. Within the LEVITATE Project, the policy intervention of Dedicated Lanes is thoroughly investigated as a sub-use case. The main objectives of this sub-use case included:

- Determining the minimum market penetration rate (MPR) required for dedicated lane to be viable option,
- Investigating the optimal configuration for dedicated CAV lanes,
- Finding the societal level impacts of dedicated CAV lanes.

2.2.1 Literature review

In principle, the concept of dedicated lanes originates from the high occupancy vehicle (HOV) and toll (HOT) lanes. This type of lanes was reserved for the exclusive use of vehicles with a driver and one or more passengers including carpools, vans, and transit buses. The first application of HOV lane can be placed around the 1970s. In theory, the implementation of this type of lanes was supposed to encourage people to car share and car-pool. However, the evaluation of the HOV lanes showed that they were underutilised and hence the concept of HOT lanes was introduced where single-person vehicles are allowed to drive in these lanes if they pay a fee. Another type of lane that has been discussed in relevant literature over the years is electric-vehicle only lanes, an intervention that could provide incentive to buy an electric vehicle.

Dedicated AV lanes have been the topic of research for several research papers and European literature (Mohajerpoor & Ramezani, 2019; Vander Laan & Sadabadi, 2017; Ye & Yamamoto, 2018). Theoretically, the introduction of dedicated AV lanes is supposed to provide an incentive to people to buy an automated vehicle and, especially during the first years of AV implementation, limit the interaction between humans and AVs which could be proven problematic. In this regard, literature review was performed to identify various lane allocation strategies under different fleet compositions, and their resulting traffic performance.

Mohajerpoor and Ramezani (2019) analysed the characteristics of mixed-traffic flow of AVs and NVs (Normal Vehicles) on arterials and highways to model the impact of AVs on saturation flow rate using analytical models to determine headways and their variability. As part of this study, the impact on delays on a two-lane road under various lane allocations, including dedicated AV lanes, was also investigated. In total, four lane allocation policies were analysed for their delay effects on the specified two-lane link road: (a) dedicated lanes (one AV, one normal vehicle (NV)), (b) mixed-mixed lanes (both lanes for mixed traffic), (c) mixed-NV lanes (one for NV and one for mixed traffic), and (d) mixed-AV lanes (one for AV and one for mixed traffic). The best lane-allocation policy was found to be the mixed-NV lanes policy when the expected penetration rate (ERP) is less or equal to 50%; the dedicated lanes policy for 50%< EPR <65%; and the mixed-AV lanes policy for 65% EPR 100%.

Previously, autonomous vehicle behaviour has been modelled at the macroscopic level in a study by Vander Laan and Sadabadi (2017), which considered the impact of the operational performance of autonomous vehicles (AV) on a multi-lane freeway corridor with separate lanes dedicated to AV and non-AV traffic. Newell's linear car-following model is used and applied to a 22 mile stretch of the 4-lane I-95 corridor between Washington, DC and Baltimore, MD during the afternoon peak period (1600-1800), when congestion levels are generally high. The impact of introducing an AV-only lane is assessed at numerous AV penetration rates, with Vehicle Hours Travelled (VHT), Vehicle Miles Travelled (VMT), average speed and vehicle throughput all are plotted against AV penetration rate. Under one AV dedicated lane, the results showed that as penetration rates increased up to 30, 40 or 50%, overall corridor performance metrics (VHT, VMT, speed, throughput) improved; however, further AV penetration considerably worsened the overall traffic performance.

Ye and Yamamoto (2018) presented a study to analyse the behaviour of CAVs in mixed traffic conditions with a dedicated lane through fundamental diagrams. A cellular automaton (CA) model was developed with no specific road environment but using the penetration rates, densities, dedicated lane numbers and determine the impact on flow. The results indicated degradation in the performance of the total traffic flow throughput with CAV dedicated lanes at a low CAV penetration rate, particularly at a low-density level. At higher penetration rate, the benefits of establishing dedicated lanes were found to diminish as well. Their findings suggested that benefit of providing a dedicated CAV lane is only achievable within a moderate density range. The penetration rate of CAVs and their individual performance are critical elements in determining the performance of a CAV dedicated lane. The higher the performance of the CAV, the more value it will derive from the implementation of a CAV dedicated lane. Additionally, the performance of the CAV dedicated lane can be increased by requiring CAVs to go at a faster speed than vehicles on other conventional lanes.

Ma and Wang (2019) studied the impact of CAV dedicated lanes on traffic flow in heterogeneous traffic condition. A cellular automata model is used as the car-following (longitudinal) and lane-changing (lateral) model in this study and a one-way four lane scenario was modelled, based on a freeway similar to Interstate 15 north of San Diego. The paper verifies that setting up exclusive lanes for CAV will greatly improve the traffic condition of the freeway under different penetration rates of CAV. However, when the proportion of CAVs is much less or much higher, the dedicated lanes do not show great impact on capacity. Based on the results on traffic flow, the study suggested one dedicated lane to be the most suitable option under CAV penetration rate ranging from 10 to 40%. Whereas with further increase in CAVs percentage i.e., 50-90%, two dedicated lanes were recommended as the optimal option.

In many studies identified across this literature review, two and four lane freeways/motorways were used in the simulations, and speed, speed variances, travel time and traffic density were identified as the main impacts, with penetration rates of between 30-60% leading to the best outcomes for the impacts (e.g., faster travel times, speeds, and minimal speed variance). The findings also suggest that one dedicated lane may be a suitable option only under low to medium MPR scenarios (10- 40%) and for higher MPRs two dedicated lanes or maybe a dedicated lane for HDVs could be a viable option.

2.3 Parking price policies

In the stakeholders' reference group meetings, there has been a special emphasis on parking space management within CATS. Following that this sub-use case investigates various possible interventions related to parking to analyse various impacts within LEVITATE project.

2.3.1 Literature review

Parking price is one of the important factors for deciding personal vehicle use as a mode of transportation. Currently there are around 30million cars in Great Britain (Department of Transport, 2017). As the number of cars increases, the need for parking spaces will increase. Parking spaces may not be always available, so policy makers want to reduce the demand for parking spaces as well as low occupancy cars. This is one of the reasons for implementing the parking prices (Institute for Transport Studies, 2019).

It is not necessary for autonomous vehicles to park near the destination or park at all. Hence this could solve the problem of parking. As autonomous vehicles do not require parking, then they could do one of the following actions: i. roam around until the passenger needs them again, ii. they can go back to origin and park outside, iii. there could be an intermediate situation (balanced) where some of the vehicles may return to the parking, and some remain in the network.

The strategy of increased parking prices to reduce parking behaviour is not new. These have been implemented since the 90s for better management of spaces. A survey of UK local authorities by Healey and Baker (1998) revealed that at that time, 25% of the authorities were trying to cut parking spaces. Whereas around 50% of them were planning to increase the parking price.

A study by Simićević, Vukanović, and Milosavljević (2013) used a stated preference survey to quantify the effects of parking price on the use of parking spaces. The authors developed the relationship between parking price and time limitation. It was found that parking price affected car use, whereas the time limitation decides whether people use on-street or off-street parking. Further, it was also found that parking price could help manage the parking spaces and it could also destroy the attractiveness of some zones. Studies also show that the parking price could affect the travel time (Qian & Rajagopal, 2014).

Millard-Ball (2019) applied a traffic microsimulation model based on the real traffic data from the San Francisco County Transportation Authority. The results showed that the reduced price of parking could add more trips by car due to vehicles cruising and avoiding parking, which resulting in increasing congestion and VMT.

Parking price is one of the deciding factors in whether to use personal vehicles or not. Hence, parking prices may affect the overall traffic flow on the roads and could affect emissions and safety. Moreover, it is known from older studies that parking can significantly affect traffic safety (Humphreys, Wheeler, Box, & Sullivan 1979), hence the implementation of traffic safety management measures is required (Cao, Mihwa, Wakita, Morikawa & Liu 2017). The parking price is one of the measures agencies take to control the traffic demand. Further, the effect of autonomous vehicles on safety is one of the major concerns to the researchers, and a lot of research in general is continuing in this direction. To examine the effects of various urban form elements on vehicle travel and carbon emissions, Frank, Greenwald, Kavage, and Devlin (2011) used thorough data on several urban form characteristics. According to their findings, increasing parking costs from $0,28 to $1,19 per hour (50th to 75th percentile) lowered VMT by 11,5% and emissions by 9,9%. Furthermore, Litman (2021) specifies that the parking price could reduce a potentially large number of conflicts leading to a higher safety.

Mei, Feng, Kong, Zhang, & Chen (2020) proved that the reduced parking costs can increase traffic congestion, which can increase the total distance travelled. The authors have also demonstrated that a $1 increase in parking price can reduce the trips from 1.5 to 2 times (Harvey & Deakin, 1998). Similarly, other studies have demonstrated that a 10% increase in the parking price would reduce the parking demand by an average of 3% (Kelly & Peter, 2006; Gillen, 1977; Kulash, 1974). Hence, the parking prices could potentially reduce the congestion, VMT, emissions and other externalities (Alavi, 2016).

In summary, parking prices are introduced to reduce the personal and single occupancy vehicles on the roads. These strategies also help in increasing the traffic flow, decreasing the travel time (Qian & Rajagopal, 2014), and improving the safety of vehicles. Further, the imposition of these also decreases VMT and emissions (Alavi, 2016).

2.4 Parking space regulations

On-street parking is the most common parking method that comprises of all paid and unpaid parking activities along the roadside in urban cities (Biswas, Chandra, & Ghosh, 2017). It allows drivers to park their vehicles close to their destination and share the same road width with other vehicles moving on the street (Prakash, Bandyopadhyaya, & Sinha, 2020). On-street parking has some natural contributions to the economy. However, the negative effects have drawn attention from governmental bodies and academic institutions in terms of causing congestion, capacity reduction and increasing road traffic accidents. Theoretically, the introduction of autonomous vehicles offers the potential to improve road safety and reduce the urban space requirements for roads and parking, and this opens up new opportunities to create more space for high-quality and liveable areas (González-González, Nogués, & Stead, 2019; 2020).

2.4.1 Literature review

Within D6.3, medium-term impacts have been defined as those at system level related to congestion, amount of travel, model split using public transport, model split using active travel, shared mobility rate, vehicle utilization rate and vehicle occupancy. This part of literature review is directed towards the findings from previous studies on the corresponding indicators.

On-street parking has a high association with traffic congestion. According to Biswas, Chandra, and Ghosh (2017), on-street parking normally reduces the road capacity in two ways and eventually contributes to the capacity loss of urban roads. Firstly, on-street parking narrows down the carriageway width and vehicles are forced to move into this reduced carriageway. This leads to a reduction in overall stream speed. Secondly, frequent parking and unparking manoeuvres creates congestion on the roads. Hence, up to 90% of the capacity reduction was reported in the study as a consequence of the on-street parking. A study from Fadairo (2013) indicated that nearly 14% of all congestion on urban roads were caused by on-street parking or parking manoeuvring vehicles. Guo, Gao, Yang, Zhao, and Wang (2012) observed that traffic volume decreases when the proportion of parking manoeuvres was increased, and 35% of parking manoeuvres can eventually reduce the capacity up to 35%.

There are a number of studies that investigated the relationship between on-street parking and traffic delay. Nahry, Agah, Thohirin, and Hamid (2019) examined the effect of on-street parking in Jakarta by modelling the relationship between various variables (i.e., parking turnover, parking index, flow-in and flow-out). The modelling results showed that the variable of parking turnover has a significant impact on the traffic delay. In other words, the higher the volume and the parking turnover, the higher the delay will be. A similar finding was reported by Borovskoy and Yakovleva (2017). The authors developed a dynamic simulation model that integrated AIMSUN software with Vehicle Tracking application for AutoCAD to study parking turnover impact on traffic flow delay. The results revealed that the increase in the on-street parking turnover led to an increase in traffic delays. Sugiarto and Limanoond (2013) examined the impact of on-street parking manoeuvre on travel speed and capacity, particularly on urban artery roads in the city of Banda Aceh. The traffic simulation showed that with the presence of on-street parking, the average delay time was increased by 32% and the speed was reduced by 24%.

Several previous studies have also indicated that the stream speed reduction on urban roads was an immediate consequence of parked vehicles (Biswas, Chandra, & Ghosh,2017; Kladeftiras & Antoniou, 2013). A recent study conducted by Praburam and Koorey (2015) has reported that on-street parking has a significant impact on traffic speed. The results showed that the mean speeds were reduced by around 10km/h between empty and full on-street parking levels and fell at a rate of 1km/h for an increase of 10% in the parking levels.

With regard to demand for parking spaces, various research studies indicated that the introduction of autonomous vehicles has the potential to reduce the urban space requirements for roads and parking (Lyon et al., 2017; Cavoli, Phillips, Cohen, & Jones 2017; Anderson, Nidhi & Stanley 2014; Chapin et al., 2016; Fagnant, Kockelman, & Bansal, 2015), and creating more space for the high-quality, liveable area (Gonzalez, Nogués, & Stead 2020; 2019). This was particularly in the context of shared autonomous vehicles (SAVs) that could reduce the number of the required parking spaces due to the SAVs which will be serving customers at different times (Othman, 2021). Consequently, a large number of existing parking spaces will be gradually removed or replaced and converted for other purposes, such as green and recreational spaces (Xia et al., 2021; Milakis, Arem & Wee, 2017; Chapin et al., 2016).

Meanwhile, automated ride-sharing services can play a vital role. Multiple studies have investigated the potential impacts of shared autonomous vehicles (SAVs) and indicated SAVs could significantly reduce the demand for private vehicles, resulting in fewer parking spaces and land use due to the SAVs serving customers at different times (Othman, 2021; Xia et al., 2021; Martinez & Viegas, 2017; Milakis, Arem & Wee, 2017; Anderson et al., 2014; Alessandrini, Cattivera, Holguin, & Stam 2014; Fagnant & Kockelman, 2015; Zhang & Guhathakurta 2017). A recent study conducted by Xia et al. (2021) reviewed the current research on urban public parking spaces under the scenario of SAVs and proposed four key issues which involved: (a) how much to renew, (b) when to renew, (c) what to renew and (d) how to update. The main finding was that a large number of the parking spaces would be renovated and transformed for other uses in the SAV era.

A report conducted by International Transport Forum (2015) investigated the microsimulation of the SAVs in the city of Lisbon, Portugal. The results showed that under a fully shared automated vehicle fleet scenario, both on-street and off-street parking spaces could be significantly reduced between 84% and 94%. A similar finding by Zhang and Guhathakurta (2015) used an agent-based simulation model to quantify the space saving, the results indicated that the parking space required for the participating clients can be reduced by over 90% once the SAV system is implemented. The results also indicated that the amount of the urban parking spaces saved can be converted to more sustainable designs, such as more green, open, and human-oriented spaces.

A study by Silva, Földes and Csiszár (2021) investigated the transformation between SAVs and urban spaces. The authors applied the method of building scenarios in a case study in Budapest, Hungary. The results indicated that almost 83% of the parking demand could be reduced and this amount of the urban spaces can be renovated for other purposes. The results also showed that SAVs can significantly minimise air pollution caused by parking infrastructure and up to 45% reduction can be achieved.

Zhang and Guhathakurta (2017) proposed a discrete event simulation (DES) model based on the real transportation network with calibrated link-level travel speeds and a travel demand origin–destination matrix. The study attempted to examine the impact of SAVs on urban parking land use in the city of Atlanta, Georgia. The results revealed that nearly 5% of parking land can be reduced by the SAV system at a 5% market penetration level. The results also indicated that each SAV can emancipate more than 20 parking spaces in the city.

A number of studies attempted to predict the impacts of on-street parking using traffic simulation approach, especially in the context of autonomous vehicles (such as Chai, Rodier, Song, Zhang, & Jaller, 2020; International Transport Forum [ITF], 2018; Biswas, Chandra, & Ghosh, 2017). A study by Chai et al. (2020) used the SUMO traffic model and local travel activity data to simulate AV parking scenarios in the central business district (CBD) of San Francisco. In the study, three scenarios have been simulated: (a) demand for drop-of and pick-up travel versus parking; (b) the supply of on-street and off-street parking; and (c) the total demand for parking and drop-of and pick-up travel due to an increase in the cost to travel. The results showed that the shift from parking trips to drop-of and pick-up trips improves traffic flow due to reduced parking search time and more efficient use of parking spaces. The results also indicated that over-allocation of drop-of and pick-up spaces could further increase CO_2 emissions from vehicles that get stuck in traffic congestion. and suggested such convention of parking spaces to drop-of and pick-up spaces must be street specific and dynamic over-time to adjust to the changes in AV market shares.

A study conducted by International Transport Forum (ITF, 2018) provided a modelling exercise to quantify the impact of re-allocating curb space from parking to pick-up and drop-off zones for passengers and freight in an area of central business district (CBD) of Lisbon, Portugal. The results showed that the curb-release lay-bys have a better fit between the supply and demand for pick-up/drop-off capacity and have a significant reduction on queuing and resulting delays. The results also suggested that city councils should consider how to dynamically manage the spaces from the street to the curb over the course of the day.

According to the findings from the previous researchers on-street parking can potentially cause some negative impacts on traffic performance in the urban area, i.e., by reducing road capacity, increasing delay time, and causing congestion. The introduction of connected and autonomous vehicles could have the potential to mitigate some of the negative impacts with suitable on-street parking regulations. The previous studies also suggested that the on-street parking spaces should be more dynamically managed and re-used.

2.5 Automated ride sharing

Ridesharing is a conventional model where the private car is shared via pre-arranged journeys. Ridesharing is pre-arranged within, for example, neighbourhoods, community, the workplace, or informally via ride-matching web and apps.

Sharing taxis has been done informally at taxi stands by identifying similar destinations via 'word of mouth'. However, app-based taxi sharing is an emerging business model where the user can call a taxi via the app and share it with others if they wish to. Ride matching is handled by optimising algorithms and matched ride options are available to users via apps. CCAM will play a significant role in this model as connectivity will enhance the taxi sharing options, and automated vehicles are speculated to reduce taxis' costs.

However, it is important to identify that micro-transit services on-demand and on demand mini-bus services can be operating along fixed or flexible routes based on demand. These are usually commercial services, and the number of seats is usually greater than taxis. This option seems to overlap with the urban shuttle sub-use case within the LEVITATE project and does not seem to be a passenger car sub-use case.

Out of these options, it has been recognised that automated taxi sharing is the fastest emerging business and is already in operation in many cities worldwide. Considering the suitability under the passenger transport use case, automated taxi sharing was taken forward as one of the sub-use cases to investigate within this work package.

2.5.1 Literature review

The emergence of autonomously driven vehicles holds great promise for the future of on-demand shared mobility services. On-demand mobility services, such as car-sharing, ride-hailing, and ride pooling, have gained increased popularity over the past few years. Due to becoming an increasingly common travel solution, such mobility services are causing a dramatic change in the mobility behaviour of the users, especially in urban areas. On-demand mobility services can positively impact transportation, land use, the environment, and society, and combining them with the emergent technology of autonomously driven vehicles could amplify these benefits.

In this regard, a comprehensive review of relevant studies in the field of Shared Autonomous Vehicles (SAVs) was presented by Narayanan, Chaniotakis, and Antoniou (2020). The authors discussed SAV services from different aspects, including service typology, characteristics, modelling, and potential impacts. They found that most studies showed an increase of mobility and an increase of efficiency for the transportation system. A comparison of the studies over the years was also undertaken and further showed the change in impacts due to of certain variables. For example, a decrease was found in the potential of SAVs to reduce parking requirements between 2015 and 2018. It also appeared to be the case that shared services will lead to a modal shift from public transport, and so SAVs would need to be integrated efficiently with public transport in the future. The authors also that assumptions within the previous studies are often based on current travel data rather than being based on future projections. In order to realistically understand the impacts of introducing SAVs, scenarios need to be based on plausible assumptions that may occur in the future. From the review it was found that main areas for SAVs where there is a lack of research include fleet size, elasticity, short-term car sharing systems, dynamics pricing, social equity, and public health.

It is also important to predict the potential impacts of shared autonomous mobility services on travel behaviour and land use. In this context, Soteropoulos, Berger, and Ciari, (2019) presented their findings through a review of modelling studies investigating the impacts of SAVs on travel behaviour and land use. The review found that shared AV fleets could have positive impacts, reducing vehicles numbers and parking spaces as well as VHT. However, there could also be a potential for a slight increase in the inner-city populations. The results also suggested that in rural areas, a greater number of vehicles may be needed to replace the current fleet due to more empty rides. The authors indicated the need for more research on empirical travel costs and perception of time in AVs, especially with shared rides. Additionally, future issues that need to be considered include the social-emotional matching of passengers in ride-sharing, acceptance of long trip durations due to picking up other passengers, longer waiting times and the types of vehicles (e.g. sizes) changing due to the changes in functions.

With regard to extra vehicles miles (VMT) travelled, Fagnant, Kockelman, and Bansal (2015) investigated the potential implications of a virtual shared autonomous fleet in a 12 x 24mile area of Austin, Texas. The authors assumed that a 1.3% share of the total regional trips are going to be served by SAVs and performed the simulation using MATSIM dynamic traffic simulation software under different traffic conditions during the daytime using 5-minute departure time windows. They concluded that each SAV could replace approximately 9.3 conventional vehicles while being able to maintain a good level of service and having an average of 1 minute user wait time. In terms of distance travelled, the results showed the new service generate around 8% extra VMT due to pick-up and relocation empty trips. The results also showed that in spite of the additional VMT, SAV deployment will probably have a positive impact on emission and air quality since SAVs are supposed to be modelled as environment-friendly vehicles with a high turnover rate and less cold starts.

Oh et al. (2020) investigated the potential impacts of AMOD (Automated Mobility-On-Demand) on transportation in Singapore in 2030 using activity and agent-based simulation (on the demand side and the supply side, plus their interactions). The scenarios and performance measures used in the study included mode availability (all existing modes such as walking, car, car-pooling, bus, cycling etc, plus MOD and AMOD-single and shared), pricing (75%, 100% & 125% of existing taxis), fleet sizing and performance measures such as demand patterns (mode shares/shifts), network performance (vehicle km travelled, trip times, Travel Time Index) and AMOD service metrics (request satisfaction rates, vehicle utilization, average waiting times). The main findings were that AMOD use is likely to be greater than existing MOD and taxi services, but there was found to be an increase in Vehicle Kms Travelled of up to 17% when there was moderate adoption of AMOD and total vehicle ownership was not capped. The fleet size needed to serve AMOD demand across an island the size of Singapore would range from 27500 to 43200, which is more than an on-demand or taxi fleet.

In terms of the benefits and costs of SAVs, Gurumurthy, Kockelman, and Simoni (2019) performed an analysis across Austin, Texas, through agent-based using MATSim, replicating the travel patterns in Austin, Texas with personal and shared AVs, and Dynamic

Ride Sharing (DRS) and road pricing policies in use. The impacts of fleet size, pricing and fare levels were scrutinized, with the results showing that inconvenience and privacy issues were overcome by the cost-effectiveness of travelling with strangers when fares were at a low-medium level. Lower fares for those using Dynamic Ride Sharing appeared to increase passenger's willingness to share rides and therefore resulted in a higher Average Vehicle Occupancy. Regarding fleet size, the results indicated that larger SAV fleets would increase single occupancy, leading to a reduction in DRS value. Therefore, in the future, operators should aim to have a moderate (rather than high) fleet size and keep fares relatively low to ensure the maximum benefits, which should limit any effects on rising traffic congestion.

In order to identify the overarching advantages and disadvantages of ride-sharing, Lokhandwala and Cai, (2018) used agent-based modelling with New York city data. A comparison of traditional taxis with shared automated taxis was undertaken. A potential fleet size reduction of 59% could be achieved from the switch to shared automated taxis from traditional taxis without any significant increase in wait time for occupants. The main benefits highlighted were increased occupancy rates, reduced travel distances, reduced carbon emissions and increased system flexibility. One disadvantage highlighted was that a reduced fleet size caused by dynamic ride sharing could lead to taxis focusing on higher demand areas, so some areas would be left with limited services, particularly in the suburbs.

The effects of trip densities and parking limitations on shared autonomous fleet performance were the focus of the study by Yan, Kockelman and Gurumurthy (2020). MATSim is used to micro-simulate the 7-county Minneapolis – Saint Paul region of Minnesota, USA. Various trip densities (2%, 5%, 20% of total trips), parking constraints (kerb parking everywhere, kerb parking restricted) and fleet parameters (SAVs per traveller) are investigated, with and without DRS being enabled. With DRS, SAV VMT reduced by 17%, with 'empty' VMT being reduced by 26%. Parking restrictions led to a greater VMT (by 8%). Also, SAVs were found to potentially perform better in regions with a high population density and trip density with shorter trip lengths. External and commercial trips were not included in this study, and both could contribute to VMT and congestion, so this may slightly limit the validity of the result found.

Overall, the findings of the literature presented above identifies various strategies through which benefits of shared autonomous services can be maximised. In this regard, fleet size, willingness to share, and characteristics of the service area can play a key role in maintaining the potential for positive benefits. Some areas where more research is needed include, fleet size, elasticity, short-term car sharing systems, dynamics pricing, social equity and public health, travel costs, and perception of time in ridesharing.

2.6 Green Light Optimal Speed Advisory (GLOSA)

Cooperative Intelligent Transport Systems (C-ITS) functions are employed to improve traffic safety and efficiency and are realized through communication between road vehicles and infrastructure together with on-board vehicle software. Among these, there are the so-called Day 1 services that build on mature technologies and are expected to be available on the short term (Mellegård & Reichenberg, 2019).

Green Light Optimal Speed Advisory (GLOSA) is a Day 1 C-ITS signage application enabled by the C-ITS service "Signalised Intersections". The application utilises traffic signal information and the current position of the vehicle to provide a speed recommendation in order for the drivers to pass the traffic lights during the green phase and, therefore, reduce the number of stops, fuel consumption, and emissions. The distance to stop, the plans for signal timing and the speed limit profile for the area are taken into account to calculate the speed recommendation displayed to the driver. GLOSA service is provided through ETSI G5 into the on-board computer of the vehicle or via mobile network into a smartphone app.

Road transport entails undoubtfully benefits to society but does not come without externalities. The negative effects on the environment and the society include traffic crashes, pollution, and congestion (Santos, Behrendt, Maconi, Shirvani, & Teytelboym, 2010). Congestion entails interrupted flow, lower speeds, larger travel times and delays. This has an environmental impact as when a vehicle faces delays on the road, with multiple stops and waiting in the traffic lights, due to mostly speed alterations and frequent acceleration and deceleration manoeuvres, the fuel consumption and pollution is increasing.

In recent years, technological achievements have rendered vehicle wireless communications available. Connected vehicle technology includes vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication and has several safety and mobility applications (Radivojevic, Stevanovic, & Stevanovic, 2016). As traffic information becomes accessible, connected vehicles are able to adapt their behaviour according to traffic conditions which can contribute to beneficial changes in traffic flow and emissions (Masera, Imprialou, Budd, & Morton, 2019). One emerging vehicle to infrastructure application that intends to improve emissions through optimizing traffic flow on signalized road networks is the Green Light Optimal Speed Advisory (GLOSA). The basic concept and working of the system are elaborated through a schematic diagram in Figure 2.1.

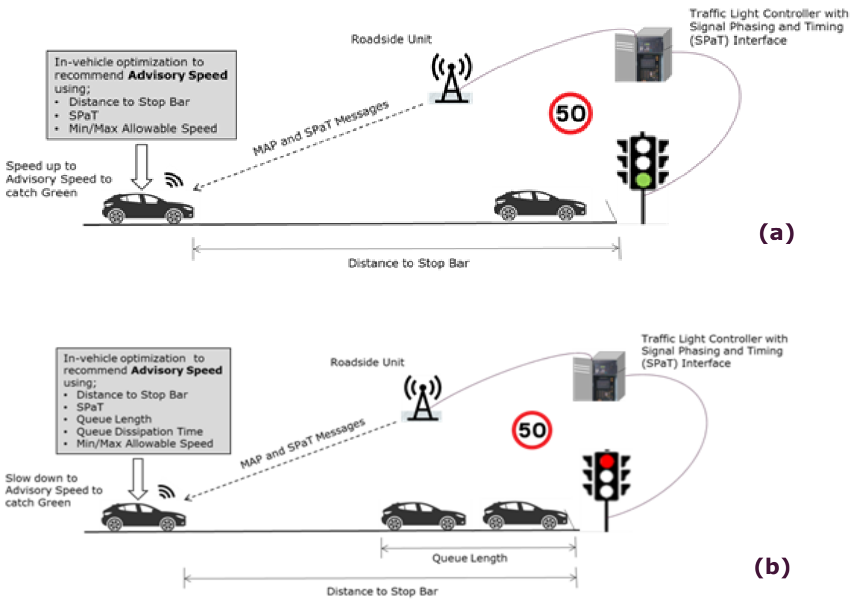


Figure 2.1: GLOSA system and application overview: (a) Communication initiated when current phase is Green, (b) Communication initiated when current phase is Red

In automated and connected vehicles era, it would be useful for cities, various stakeholders, and transport planners to assess the societal impacts of such an application in an urban area and attempt to evaluate the benefits in relation to the relevant costs.

2.6.1 Literature review

With regard to previous studies exploring the impacts of GLOSA system, Mellegård and Reichenberg (2019) provided a review of 64 publications between 2006 and 2019 investigating GLOSA (Figure 2.2). Most based their findings on simulation, with a much smaller amount using real-world methods (e.g., pilots, FOTs). The on-board GLOSA algorithm was proposed as the main solution in the majority of the studies, with less proposing the whole system and/or predicting signal changes as the solution. The focus was on the equipped vehicle in most studies, as opposed to fellow road users or other societal issues. In terms of impacts, many of the studies looked at the effect of varying traffic levels on GLOSA effectiveness. No publications examined drivers' ability to follow the advised speed. Travel time increases, as well as decreases, were seen across the 64 studies.

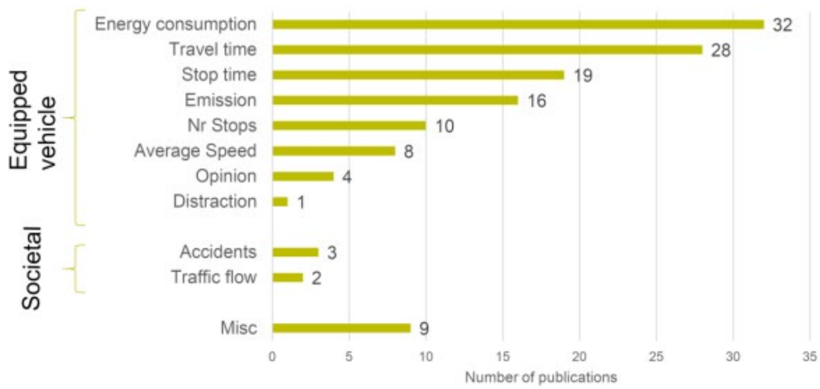


Figure 2.2: Overview of the effects/impacts evaluated across the 64 papers (from Mellegård and Reichenber, 2019)

The potentials and limitations of GLOSA systems in realistic large-scale simulations were investigated by Eckhoff, Halmos, and German (2013). This study mainly looked at environmental-related impacts (e.g., emissions), but also analysed impacts on waiting times and the number of stops. The simulation framework Veins was used, coupling OMNeT++ and the traffic simulator SUMO. An area of Munich was used to develop the simulation, and four levels of traffic density were investigated in the study; two were in free flow, one was in semi-free flow, and one was in synchronised flow. CO2 emissions were lowered by up to 11.5% in low traffic densities, waiting times by 17% and amount of stops potentially by around 6%. But in heavier traffic conditions, some issues were detected, such as longer waiting times higher CO2 emissions for non-equipped vehicles.

Gajananan et al. (2013) used an integrated traffic, driving and communication simulator to investigate the effects of GLOSA on emissions, travel times and stopped times. GLOSA introduction led to a reduction in all 3 of these areas (40-68% reduced stopped times, 10-16% reduced travel times, 8-20% reduced CO2 emission). Lebre et al. (2015), have also reported reductions in travel time through a simulation study under experimental and real traffic conditions.

Karabag (2019) modelled two intersections on a section of road in the city of Tallahassee, Florida, USA, using VISSIM simulation software. The reduction in delay was found to be significant including a decrease in stop delay by 84% and number of stops by 88%.

Previous studies have also reported that benefits on GLOSA system can be achieved if used with fixed time signal controllers. For instance, Stevanovic, Stevanovic, and Kergaye (2013), who used VISSIM simulation model of 5-intersection corridor in the US while testing fixed and actuated signal timings, found improvement in travel time, number of stops, and fuel consumption under fixed timings, but not under actuated operation. Under fixed-time controllers, the authors also reported improvement in traffic performance with higher MPR and increased frequency of GLOSA system activation. Signal retiming/optimization before implementing GLOSA was suggested as increasing the benefits from such an application.

The findings from the above literature indicate reduction in delay with application of GLOSA system particularly when used with fixed time signals. However, percentage reduction reported has been found to vary across the existing literature. Previous studies also indicated that expected benefits can be attained at low traffic densities whereas under congested traffic situations the system could be counterproductive.

3 Methods

The types of impacts that are presented in Deliverable 3.1: A taxonomy of potential impacts of connected and automated vehicles at different levels of implementation (Elvik et al.,2019) have been estimated and forecast using appropriate assessment methods, such as traffic simulation, system dynamics and Delphi panel method. For example, traffic simulation can directly provide short-term impacts. Therefore, it was used to forecast short-term impacts to be able to develop relationships that can infer dose (in terms of introduction of sub-use case) and response (selected impact). Traffic simulation also provides further input to assess medium-term impacts by processing those results appropriately to infer such impacts. System level analysis (such as by tools found within system dynamics) can provide a measure of medium- and long-term impacts. For the sake of simplicity and applicability of assessment methods, it is assumed that for the appropriate level of automation, adequate infrastructure exists. It is also assumed that the pure technological obstacles for the sub-use cases in consideration are solved. All these results relating to the relationships between sub-use cases, impacts and any intermediate parameters will be provided to WP8 of LEVITATE, which concerns the development of the LEVITATE Policy Support Tool (PST). The results will be integrated within the PST modules and functionalities so that impact assessment can be carried out by the user.

An overview of the methods used to estimate the medium-term impacts in this deliverable is presented in Table 3.1.

Table 3.1: Overview of the methods used to estimate medium-term impacts of connected and automated vehicles under WP6

Sub-use Cases	**Methods**			
	Microscopic Simulation	**Mesoscopic Simulation**	**System Dynamics**	**Delphi**
Road use pricing (RUP)		✓	✓	✓
Provision of dedicated lanes on urban highways	✓			✓
Parking price policies	✓		✓	✓
Parking space regulation	✓		✓	✓
Automated ride sharing	✓		✓	✓
Green Light Optimal Speed Advisory (GLOSA)	✓			✓

3.1 Microscopic simulation

Traffic simulation has been widely applied to estimate potential impacts of connected and automated vehicles. As identified in LEVITATE Deliverable on Impact Assessment Methods (Elvik et al.,2020), many studies have used microsimulation technique to estimate the potential impacts of CATS on traffic performance indicators. It is envisaged that microsimulation approach can be used to calculate the direct impacts of CAVs. In most cases, a commercially available traffic microsimulation tool (such as AIMSUN, VISSIM, Paramics or SUMO) is used along with an external component. The microsimulation tool is applied to represent the infrastructure and creates the traffic in the predefined road system while the external component aims to simulate the CATS functionalities.

Within WP6, traffic microsimulation approach is used to model and analyse the sub-use cases of dedicated lanes, parking price policies, parking space regulations, automated ride sharing, and GLOSA. AIMSUN Next Microsimulation tool has been used in all the sub-use cases utilising some calibrated and validated city networks including Manchester and Leicester in UK. CAV functionalities/behaviours were modelled through adjusting a wide spectrum of parameters in the simulation framework.

3.1.1 Modelling of CAVs behaviours

Two types of CAVs were considered in this study:1st Generation CAVs and 2nd Generation CAVs. Both types are assumed to be fully automated vehicles with level 5 automation. The main idea behind modelling these two types is based on the assumption that technology will advance with time. Therefore, 2nd Gen CAVs will have improved sensing and cognitive capabilities, decision making, driver characteristics, and anticipation of incidents etc. In general, the main assumptions on CAVs characteristics are as follows:

- 1st Generation: limited sensing and cognitive ability, long gaps, early anticipation of lane changes than human-driven vehicles and longer time in give way situations.
- 2nd Generation: advanced sensing and cognitive ability, data fusion usage, confident in taking decisions, small gaps, early anticipation of lane changes than human-driven vehicles and less time in give way situations.

These characteristics were defined through various model parameters in AIMSUN Next including reaction time, time gap, acceleration and deceleration characteristics, parameters related to lane changing and over taking behaviour and several others. The default car-following model in AIMSUN Next is based on Gipps model (Gipps,1981, 1986). Various parameters of the car-following model were adjusted to implement HDV and CAV behaviours. The assumptions on CAV parameters and their values were based on a comprehensive literature review, including both empirical and simulation-based studies (Cao et al.,2017; Eilbert, Berg, & Smith,2019; Goodall & Lan,2020; de Souza & Stern ,2021; Shladover, Su, & Lu 2012), as well as discussions in meetings with various experts within the project. Some guidance on the behaviours was also obtained through studies on adaptive cruise control (ACC) and cooperative ACC (CACC) systems.

Traffic impact of CAVs were assessed in mixed traffic conditions that contain, in addition to passenger cars, freight and public transport (PT) vehicles. The automation of freight vehicles was also considered; however, due to limited knowledge on automation of freight vehicles, only a few parameters were adjusted to model the behaviours of freight CAVs.

The two types of CAVs (1st Generation CAVs and 2nd Generation CAVs) were modelled to analyse the sub-use cases, details of which are provided in the following section. The deployment of CAVs was tested from 0 to 100% MPR with 20% increments as shown in Table 3.2 below.

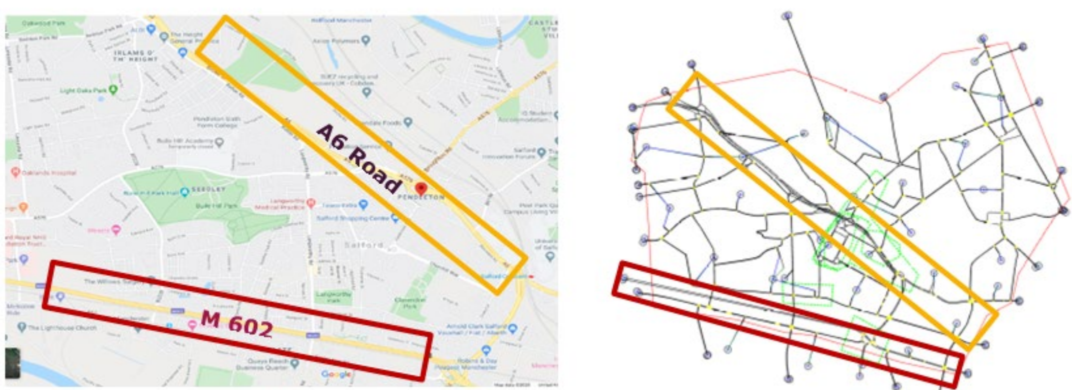
Table 3.2: CAV Deployment scenarios in LEVITATE project

Type of Vehicle	CAV Deployment Scenarios							
	A	B	C	D	E	F	G	H
Human-Driven Vehicle - passenger vehicle	100%	80%	60%	40%	20%	0%	0%	0%
1st Generation (Cautious) CAV - passenger vehicle	0%	20%	40%	40%	40%	40%	20%	0%
2nd Generation (Aggressive) CAV - passenger vehicle	0%	0%	0%	20%	40%	60%	80%	100%
Human-Driven LGV	100%	80%	40%	0%	0%	0%	0%	0%
LGV-AV	0%	20%	60%	100%	100%	100%	100%	100%
Human-Driven HGV	100%	80%	40%	0%	0%	0%	0%	0%
HGV-AV	0%	20%	60%	100%	100%	100%	100%	100%

3.1.2 Implementation based on SUC

3.1.2.1 Provision of dedicated lanes on urban highways

A calibrated and validated traffic microsimulation model of Manchester area (provided by Transport for Greater Manchester) was used for this sub-use case. In general, the model development and calibration involved details of road network in the study area, peak hour traffic demand, vehicle types, signal timing data, vehicular behaviour and lane usage, journey times, bus routes, stations, and timetable information. A comprehensive set of traffic counts was used to compare and validate the modelled flows with observed traffic counts. Modelled journey times were also compared and validated against observed journey times during the peak hours. This model provides a good foundation for the experiment as it includes a motorway and a major arterial road (M602 and A6, respectively) (Figure 3.1) which connect the centre of Manchester with the suburbs.



(a) (b)

Figure 3.1: The modelling area in the city of Manchester (a) and Manchester network in AIMSUN software (b)

Assumptions and parameters

The following assumptions have been made for this sub-use case:

- When introduced, the dedicated lane will be mandatory for CAVs and public transport. That means that the CAVs are not allowed to travel in any other lane unless they cannot follow their route in any other way.
- The dedicated lane is either the innermost or the outermost lane of the motorway or the A road according to the scenario of the sub-use case.
- The A-road consists of several consecutive segments which comprise of either two or three lanes. It is always assumed that one of these lanes is a dedicated lane, except in intersections when one cannot define a dedicated lane due to AIMSUN limitations.

Scenarios

In order to identify the most optimal strategy for providing dedicated lane which can potentially be most beneficial, the placement of dedicated lane was investigated under various scenarios including:

- Baseline scenario – AV implementation without a dedicated lane.
- Scenario 1 – CAVs use a dedicated (innermost) lane in the motorway.
- Scenario 2 – CAVs use a dedicated (innermost) lane in the motorway and the A-road.
- Scenario 3 – CAVs use a dedicated (innermost) lane in the A-road.
- Scenario 4 – CAVs use a dedicated (outermost) lane in the A-road.

These scenarios were formulated in order to address the research questions, outlined under section 2.2.

In order to address the question of what is the minimum required market penetration rate for dedicated lanes to be a viable option, several mixed fleet combinations including human driven vehicles (HDVs) and CAVs with different market penetration rate were tested in each of the aforementioned scenario.

3.1.2.2 Parking price policies

A microsimulation model of Santander City was employed for this sub-use case (Figure 3.2). Due to having the city centre area, this model served the purpose of analysing the impact of various possible AV parking behaviours due to different parking price policies. The used network model contains 108 nodes (intersections) and 382 sections (one way links). The study considers the evening peak hours (1900 - 2200) for analysis with an estimated traffic flow of 42337 private car trips.

Figure 3.2: The modelling area in Santander city (a) and in AIMSUN software (b)

This sub-use case refers to enforcing parking behaviour through different parking price policies. However, these behaviours can also be influenced by limiting parking spaces within a particular area. With automated vehicles, the widespread belief is that one would be able to command their highly automated vehicles to drive around with no occupants in them to avoid parking for a short duration. Four parking behaviours were considered for this sub-use case (Figure 3.3):

- Enter and park inside the area (baseline – consistent with the current situation),
- Enter, drop off passengers and return to origin to park (outside and inside included),
- Enter, drop off passengers and return to outside parking restriction area to park,
- Enter and drive around (short stay) vehicle drop the passenger and drive around while waiting for the passenger to ride again.

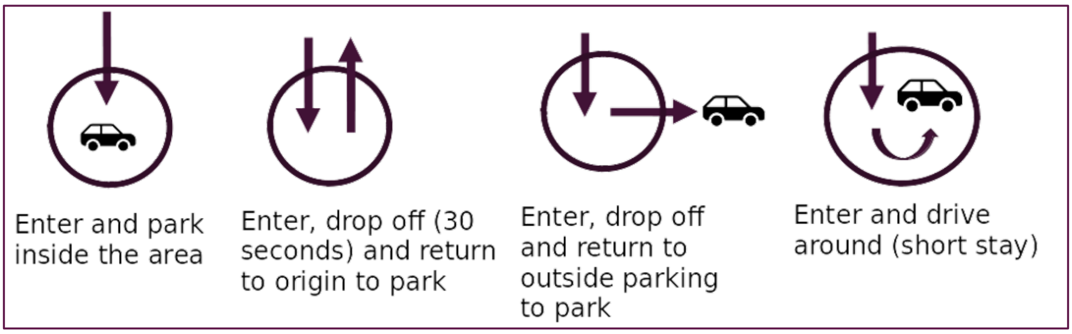


Figure 3.3: CAVs Parking behaviours

Different scenarios were considered based on the proportions of vehicles choosing these parking options (see Table 3.3). It should be noted that these percentages depend on parameters like the parking price which cannot be controlled directly in the microscopic simulation.

Table 3.3: Scenarios relating to the prevailing parking behaviours.

	Return to Origin %	Park Outside %	Drive around %	Park Inside %
Baseline	0%	0%	0%	100%
Case 1 (balanced)	22%	45%	20%	13%
Case 2 (Heavy drive around)	0%	0%	100%	0%
Case 3 (Heavy Return to origin and Park outside)	33%	67%	0%	0%

Assumptions

The following assumptions have been made for this sub-use case implementation:

- In the baseline scenario, it is assumed that sufficient spaces are available, and vehicles can park themselves inside without causing any disturbance to the traffic.
- In the 'heavy drive around scenario', vehicles drop the passenger and drive around nearby.
- In the case of 'heavy Return to origin and Park outside' vehicles do a mixed activity of parking outside and return origin.
- The 'Balanced' scenario consists of a combination of all the parking choices available.
- All CAVs are EVs.
- All human driven vehicles are non-electric vehicles.
- CAVs and human driven vehicles can travel together without any requirement of dedicated lanes.
- HGVs and LGVs are not present.
- There exist only given parking options.

Several possible compositions of modes (Human driven car, first generation AVs and second-generation AV) were considered for all scenarios for analysis (Table 3.2).

3.1.2.3 Parking space regulations

The study network used for this sub-use case is a traffic microsimulation model (developed using AIMSUN software) of the city of Leicester. Due to having the city centre area, this model served the purpose of analysing various on-street parking space regulations. The Leicester city center network is around 10,2km² and consists of 788 nodes and 1 988 sections. The traffic demand for passenger cars, LGVs and HGVs are 23 391 trips, 3 141 trips and 16 trips, respectively. The network is presented in Figure 3.4.

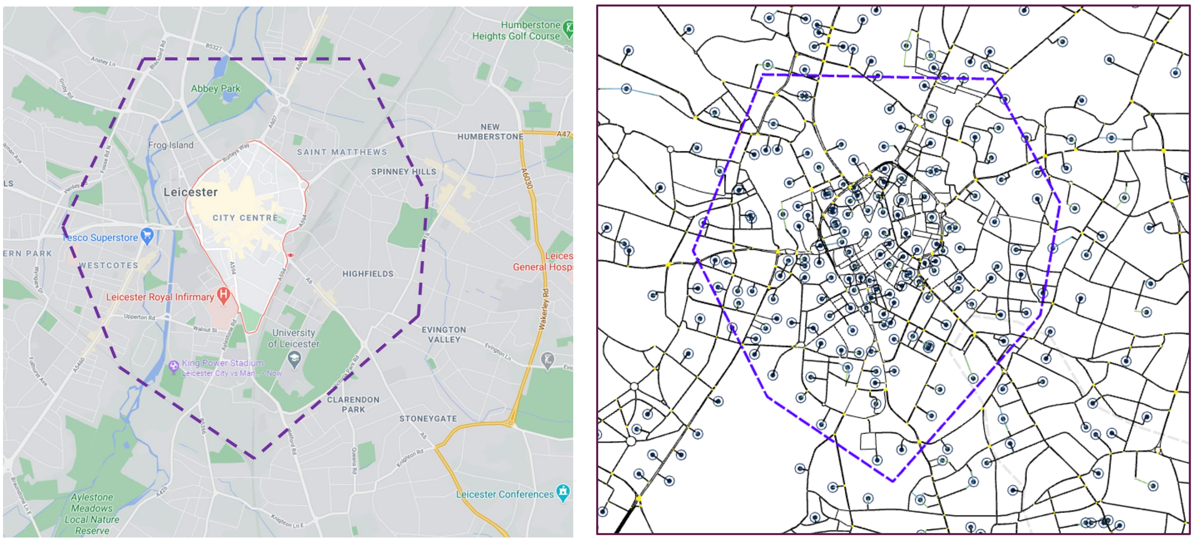


Figure 3.4: The Leicester city centre network in AIMSUN software

Scenarios

This specific network includes the city centre area only. For practical purposes to be more effective using simulation, on-street parking in the city centre has been divided into 4 parking zones, including a total of 52 streets with 138 parking bays as showed Figure 3.5.

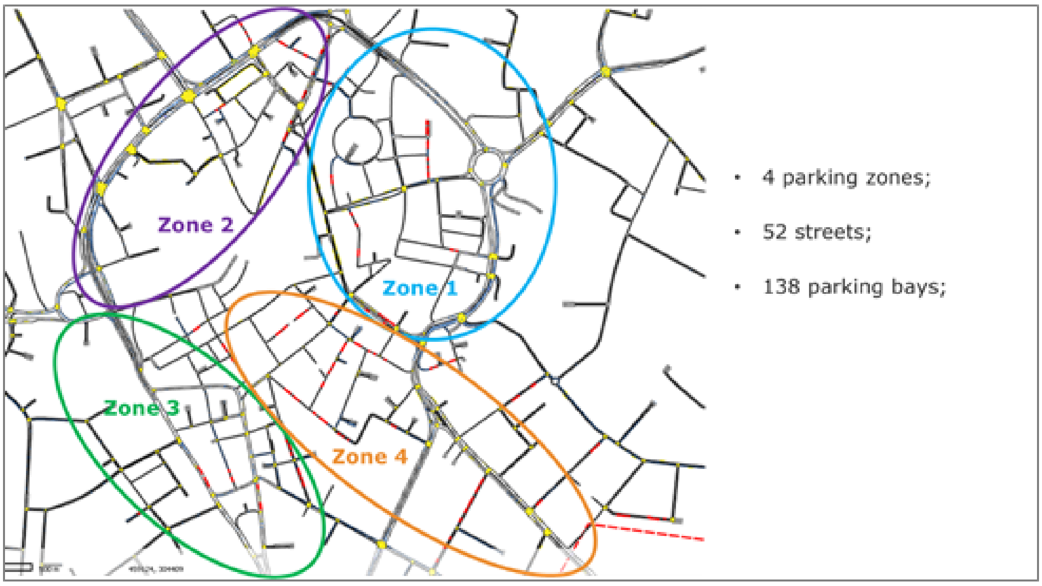


Figure 3.5: On-street parking zones in AIMSUN software

Within this SUC, six scenarios will be studied using microscopic simulation:

- Baseline scenario - CAV implementations without replacing the on-street parking intervention, CAV market penetration from 0% to 100% at 20% increments. Including a total of 52 streets with 138 parking bays for all 4 parking zones.

- Removing half of the on-street parking spaces – Scenario is based on the reduction of parking capacity, i.e., 50%. As described in the literature review section, the introduction of AVs offers the potential to reduce the urban spaces requirements for parking, the on-street parking spaces for 4 parking zones have been reduced to 28 streets and 79 parking bays, respectively.

- Replacing on-street parking spaces with driving lanes. In this scenario, on-street parking spaces will convert to driving lanes (shown in Figure 3.6).

- Replacing on-street parking spaces with cycling lanes. In this scenario, on-street parking spaces will convert to a dedicated cycle lane (shown in Figure 3.6), which means other vehicle types are not allowed to use the cycle lane. It should be noted that the cyclist behaviour has not been simulated in the modelling due to the limitation of the software.

- Replacing on-street parking spaces with pick-up and/or drop-off points (shown in Figure 3.7). The scenario assumes the AVs are shared AVs. As a result, after the vehicle pick-up or drop-off the passenger, the vehicle will exit the study area to return home or serve another customer. More detail of shared AVs can be found in automated ridesharing SUC.

- Replacing on-street parking spaces with public spaces. In this scenario, on-street parking spaces will convert to public spaces, e.g., green and recreational spaces (shown in Figure 3.6).

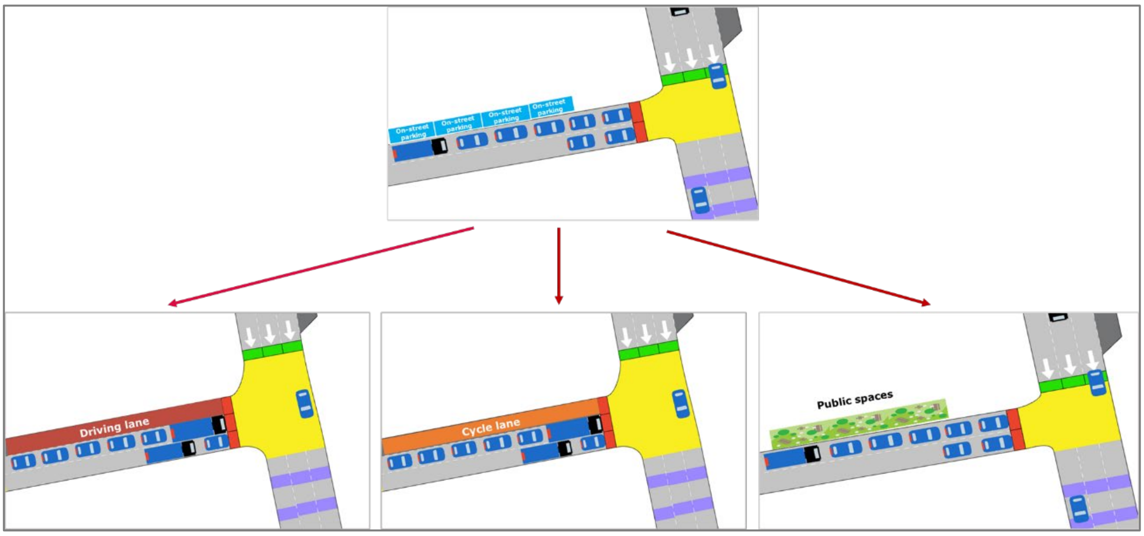


Figure 3.6: Replacing on-street parking with driving lane, cycle lane and public spaces

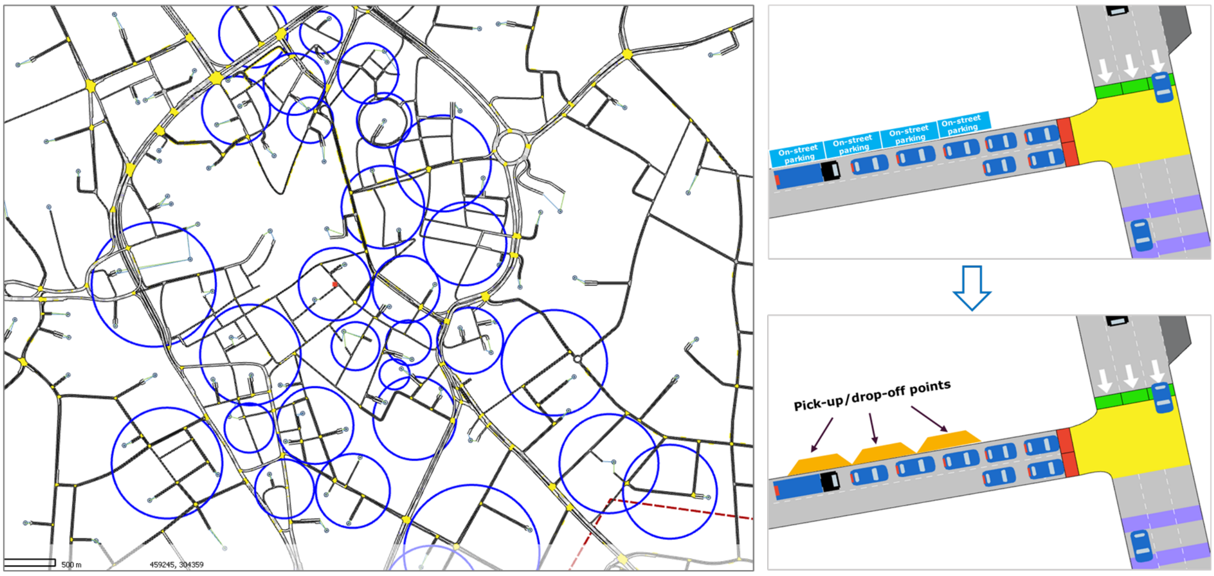


Figure 3.7: Replacing on-street parking with pick-up/drop-off points and the pick-up/drop-off locations in AIMSUN software

Assumptions

The following assumptions and limitations exist in this sub-use case implementation:

- All CAVs are assumed to be EVs,
- All human driven vehicles are assumed to be non-electric vehicles,
- Simulations are run for lunchtime rush hour, considering it to be the most critical period for this sub-use case,
- No residential parking is considered in the model,
- No changes have been considered in the disabled on-street parking bay,
- The pick-up/drop-off scenario was assumed to follow SAVs concept,
- On-street parking manoeuvre duration (blockage time) is assumed to be 30s with 20s deviation based on the previous literature (Chai et al., 2020; Chow, Rath, Yoon, Scalise, & Saenz, 2020; Fehr & Peers, 2018; Wijayaratna, 2015; Portilla, Oreña, Berodia, & Díaz, 2009),
- Cyclists are not modelled in the replacing on-street parking spaces with cycling lanes scenario due to the software limitation.

Modelling on-street parking manoeuvres

Within this sub-use case, the function of the periodic section incident has been applied to simulate the on-street parking manoeuvres (shown in Figure 3.8). It is a traffic incident that causes a lane blockage over a certain period. This action creates random incidents and are placed randomly throughout the area i.e., street, parking bay (Transportation Simulation Systems [TSS], 2021).

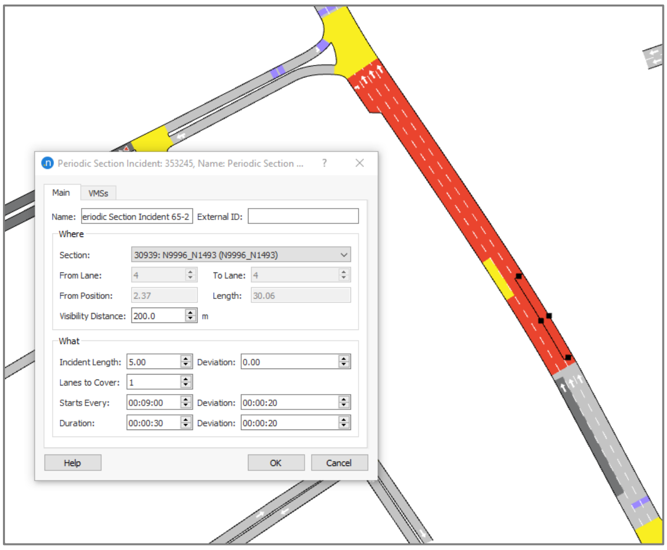


Figure 3.8: Screenshot of periodic section incident in AIMSUN Next

Figure 3.9 illustrates examples of the periodic section incident representing on-street parking on a single lane and a multi-lane road in the model using the AIMSUN Next simulation platform. The left image demonstrates the incident (on-street parking) happening on a single lane blocking the traffic over a certain time. The right image shows the incident happening on a multi-lane road where the following vehicle decides to change lane because of the leading vehicle making an on-street parking manoeuvre.

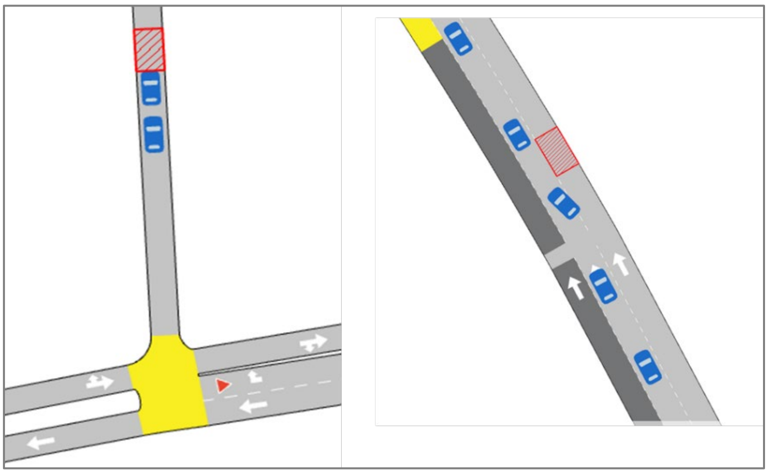


Figure 3.9: Periodic section incident on a single lane and multi-lane road in the model using in AIMSUN Next

3.1.2.4 Automated ride sharing

This sub-use case investigates the impacts of introducing autonomous shared vehicles (SAV) on the efficiency of transport systems. The proposed service combines free-floating car-sharing, ridesharing, and fully autonomous vehicles operating in Manchester (UK). With respect to operation, the proposed service is considered to provide on-demand trips where SAVs pick up passengers from their origins and drop them off at their destinations under time constraints.

In addition to passengers' origin, destination, departure, and arrival time, the SAV assignment in this sub-use case also considers the passengers' willingness to share (WTS) their rides with others which could depend on several factors such as increased travel and detour time (König & Grippenkoven, 2020) and the acceptance of sharing same vehicle with strangers (Lavieri & Bhat, 2019). The passengers' WTS has a significant impact on the efficiency of SAV service. For this reason, the impact due to this aspect is also investigated within this sub-use case.

The service introduced in this study is modelled by one of the well-known optimisation problems: the **Vehicle Routing Problem with Pickup and Delivery with Time Window (VRPPDTW)** (Mahmoudi & Zhou, 2016). With this optimisation process, trip-requests are matched to a SAV fleet (that was determined within the process), and optimised routes for SAVs are provided. The optimisation output served as an input for the AIMSUN Next Microsimulation tool to generate different KPIs to assess the impact of this service on mobility, safety, and environment. An overview of the modelling and implementation of this SUC is shown in Figure 3.10.

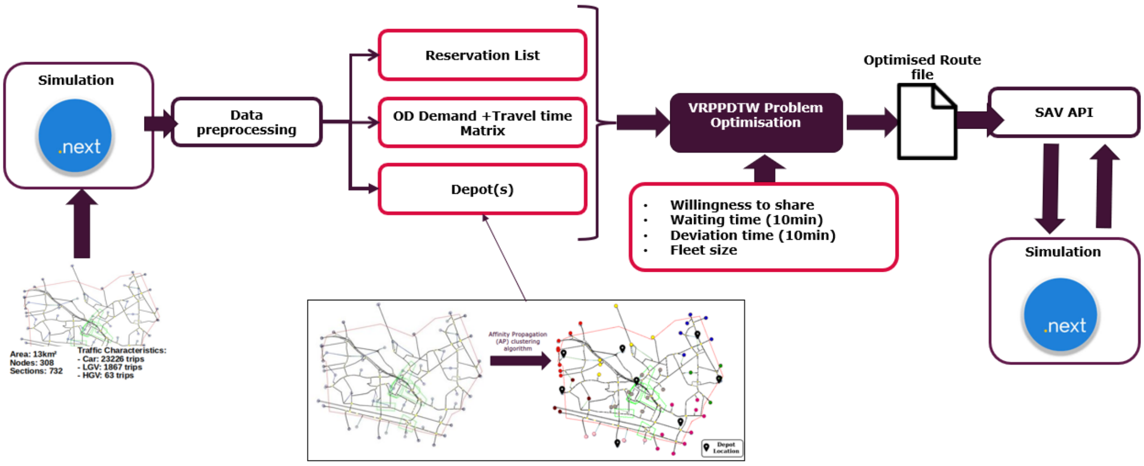


Figure 3.10: Overview of the modelling process of automate ridesharing SUC

Network Model & Data Preparation

To illustrate the potential benefits of the proposed ride-sharing service, a calibrated and validated microsimulation model (developed using AIMSUN simulation platform) was used consisting of a 13km² area from the Great Manchester Area (UK) that contains 308 nodes and 732 road sections (Figure 3.11), and OD matrix of 58x58 centroids from the network. Traffic data of evening peak hours (1700 – 1800) was used, with an estimated traffic demand of 23 226 car trips, 1 867 large goods vehicles (LGV) trips, and 63 heavy goods vehicle (HGV) trips.

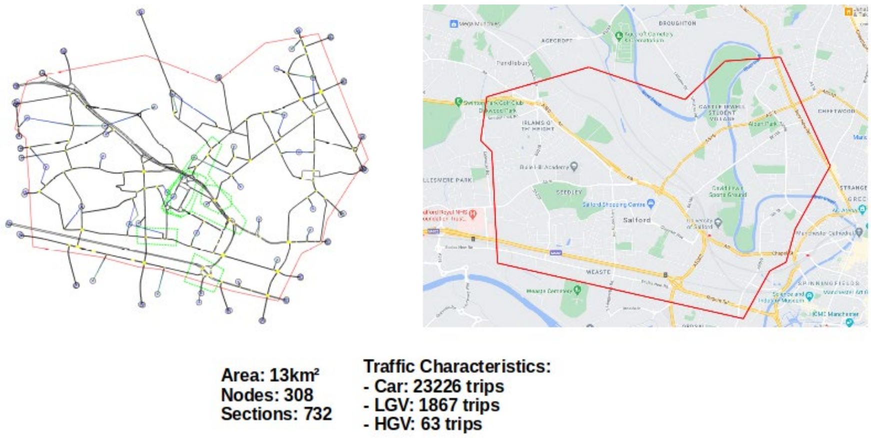


Figure 3.11: The Manchester network in AIMSUN software

As mentioned above, the proposed service is modelled as VRPPDTW problem, and to perform the optimisation process to solve this problem, a set of files have been extracted from the micro-simulation model of the study area:

- The Origin-Destination (OD) traffic demand matrix for personal car trips in the study area,
- A GIS file that contains the exact coordinates of the study area's centroids,
- Travel Time matrix with values derived from the simulation of the original OD demand,
- A list of private vehicle trips (trip ID, pickup centroid, drop off centroid, departure time, and arrival time) was also obtained from the simulation of the original OD demand.

These files hold data that will be used to generate input to the optimisation process, such as depots' locations, trip requests, pick up and drop off time windows, etc.

It was assumed that demand for this new service will replace a share of personal vehicle demand. Through the simulation of the original OD demand matrix provided with the network model, a list of trips corresponding to the personal vehicles was obtained and used to select random candidate trips that this service will perform.

Google's OR-Tools will be used to solve the VRPPDTW problem to assign routes for SAVs pickup and drop-off passengers. Each centroid in the network can be a pickup or drop-off location for several trips, which is not suitable for the OR-Tool solver that assumes each node can be visited only once and can be either a pickup or drop-off site. Therefore, to respond to this constraint, a dummy node was created for every passenger origin or destination with zero distance from the original location to distinguish pickup and drop-off nodes. Every user of this new service has a preferred time window to be picked up from his/her origin and the desired time window for arrival at his/her destination. The departure and arrival times from the list of trip requests extracted from the simulation are used as lower bounds of pickup and arrival time windows. The upper bounds values are related to the passenger's acceptable waiting time and detour from its original route (caused by ridesharing with others), and within this project, it was assumed that a passenger could tolerate waiting and detour time range from 5 min to 10 min. Instead of having fixed waiting and detour time values for all passengers, we applied a normal distribution to generate a set of values assigned to all passengers' trip requests.

Trip requests can be classified into individual or shared trips, depending on the passenger WTS. According to the literature, the acceptance of the shared trip option could be related to the user's approval of extra travel time associated with the pickup/drop-off of other passengers (König & Grippenkoven, 2020) and to his/her sensitivity toward sharing the same vehicle with other strangers (Lavieri & Bhat, 2019). To study the impact of the user's disposition to shared rides on the overall performances of the service and the network, we developed scenarios based on different aggregated levels of WTS. To facilitate the integration of this notation into the optimisation problem, it was assumed that a passenger is either willing or unwilling to share his/her ride. In other words, the passenger's decision will not be related to the value of time or money or even the number of other passengers sharing his ride. Passengers' preference for a shared ride was assigned randomly based on a predefined level of WTS. These preferences will be given as an input to Google's OR-Tools solver through a 1D array containing the demand corresponding to the number of passengers to be picked up or dropped off in each location. A positive value represents the demand at the pickup location, and a negative value represents the demand at drop-off location. If a passenger is willing to share his/her ride, the demand will be equal to the capacity of the SAV, which is assumed to be equal to regular 4-seater car; otherwise, the demand will be equal to one.

Depots Allocation

Depots and charging station locations are critical factors in deploying a ride-sharing service. In this study, the Affinity Propagation (AP) clustering algorithm (Dueck and Frey,2007) is used to determine the depots' locations. In contrast to other traditional clustering algorithms, such as K-means, the AP algorithm does not require inputting the number of clusters in advance. It determines the optimal number of clusters and their exemplars (clusters' centres) based on a message-passing procedure where all data points are considered as exemplars and exchange messages between them concerning their attractiveness and their availability to associate with other data points until an optimal set of exemplars and clusters emerges (Givoni & Frey, 2009).

The AP algorithm was implemented using python's Scikit-learn package and executed with 1000 maximum iterations taking the exact centroids' location in the Manchester network model and their corresponding total trip demand from the original OD matrix. As shown in Figure 3.12 eight clusters were determined by the algorithm, i.e., eight depots assigned to the nearest centroid from the exemplar of each cluster.

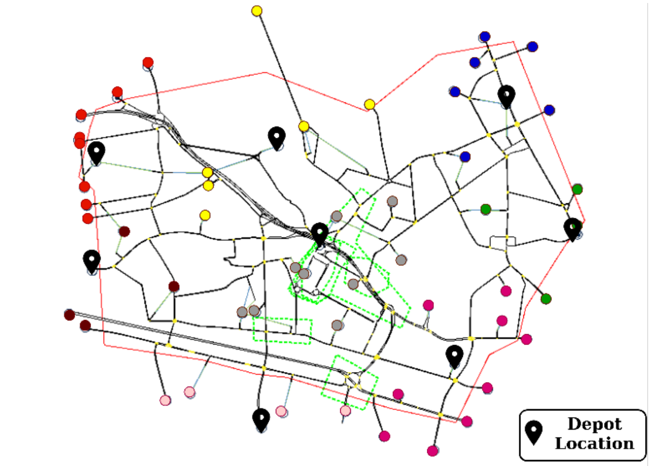


Figure 3.12: Allocation of SAV service depots based on Affinity Propagation clustering algorithm

Optimisation process

The following input data was given to Google's OR-Tools solver to solve the modelled VRPPDTW:

- The travel time matrix with values derived from the simulation of the original OD demand,
- The initial fleet size,
- The 1D demand array,
- The capacity of a SAV (4-seater car),
- The list of pick-up and drop-off pairs,
- The list of pick-up and arrival time windows, and
- The depots' locations.

The analysis was performed for the evening peak hour period (1700-1800). It was assumed that the SAVs were not required to return to their depots, but instead, they ended their routes at their last drop-off location, which was represented by the arbitrary ending depot location, which had zero distance from every other centroid. Regarding the initial fleet size, a SAV fleet equal to the served demand was assumed to be parked at each depot to ensure that every trip request is assigned to a SAV.

The maximum travel time for each SAV was set to one hour to ensure that SAVs finished their optimised routes within the simulation period. Moreover, a limit of 1000 solutions was set for every scenario to prevent the solver from running indefinitely due to the size of the optimised problem, while sufficient investigation of the solution space will take place.

Scenarios & Assumptions

Within this sub-use case, the impact of automated ride sharing is studied under the scenarios resulting from the combination of different rates of demand rates that will be served by SAVs (5%, 10%, 20%) and the percentage of travellers willing to share their rides (WTS):

1. No policy intervention: baseline scenario of increasing penetration of automated vehicles without an automated ridesharing system,
2. 5% demand for shared AVs: 5% of the total private vehicle travel demand (trips) is replaced by SAVs trip, with a variable WTS (20%, 50%, 80%, 100% of travellers),
3. 10% demand for shared AVs: 10% of the total private vehicle travel demand (trips) is replaced by SAVs trip, with a variable WTS (20%, 50%, 80%, 100% of travellers),
4. 20% demand for shared AVs: 20% of the total private vehicle travel demand (trips) is replaced by a SAVs trip, with a variable WTS (20%, 50%, 80%, 100% of travellers).

For all scenarios, deployment of CAVs in the network was tested from 0% to 100% in 20% increments with the two types of CAVs presented in section 3.1.1.

The SAV capacity considered in this SUC is four passengers, and the SAV fleet composition includes 1st and 2nd Generation CAVs. The presence of each type is based on its market penetration rate defined in Table 3.2.

The following assumptions have been made for this sub-use case implementation:

- All CAVs and SAVs are EVs,
- The battery capacity can support full-day operations for each SAV,
- Parking spaces are enough for all SAVs in each station,
- The pick-up and drop-off locations and behaviour will not be addressed in this sub-use case,
- Preference for ridesharing is presented as a parameter with two statuses (Yes, No),
- Cancellation of assigned SAV is not allowed,
- An SAV request refers to one traveller.

Optimisation Results

Table 3.4 the optimisation results for the different scenarios studied within this SUC. The results indicate that the fleet size required to replace conventional personal vehicle trips gradually decrease as more passengers are willing to share their rides. The decrease in the number of required SAVs is associated with an increase in the number of vehicles conventional that one SAV can replace.

Table 3.4: Optimisation results for automated ride sharing service

Demand to be served	Trips to be served	Willingness to share	Optimal SAV Fleet size	SAV Replacement Rate *
5%	1134	20%	645	1,8
		50%	570	2,0
		80%	490	2,3
		100%	435	2,6
10%	2239	20%	1154	1,9
		50%	1009	2,2
		80%	839	2,7
		100%	720	3,1
20%	5070	20%	2391	2,1
		50%	2067	2,5
		80%	1694	3,0
		100%	1436	3,5
(*): Number of personal vehicles replaced by one shared AV (SAV)				

Regarding travelled distance, Figure 3.13 shows that a higher willingness to share reduced the total and empty travelled distance covered by the SAV fleet in all scenarios. The results also revealed that with higher demand, the distance will be gradually increased. This increase is obtained not just because of serving more passengers but also because of the empty repositioning trips that SAVs need to perform to pick up passengers that represent a significant share of the overall trips, as seen in Figure 3.14.

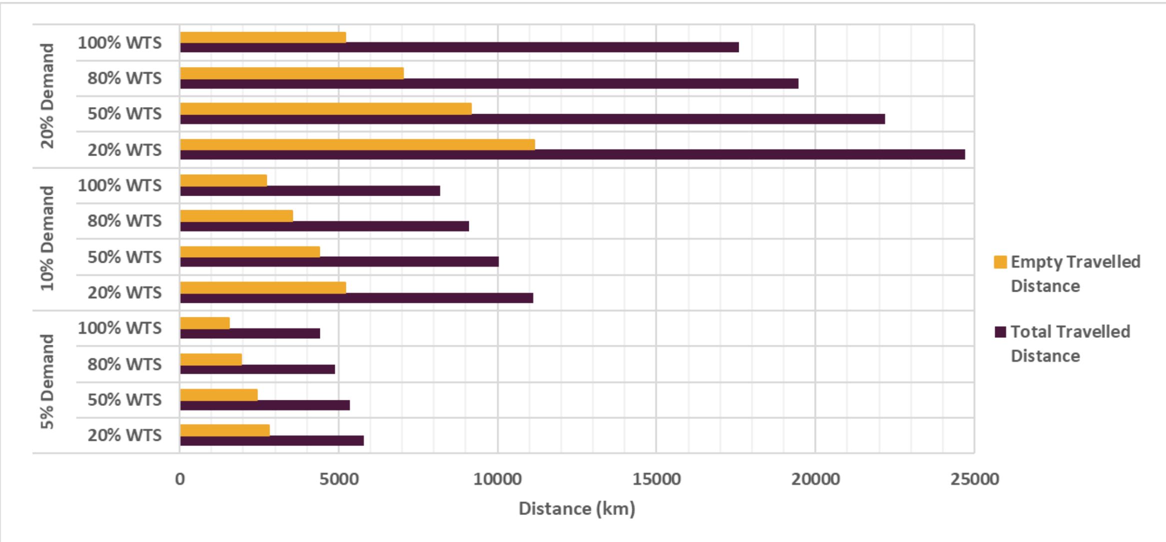


Figure 3.13: Total distance travelled by the shared autonomous vehicle (SAV) fleet in kilometres with different served demand and passengers willingness to share (WTS) percentages

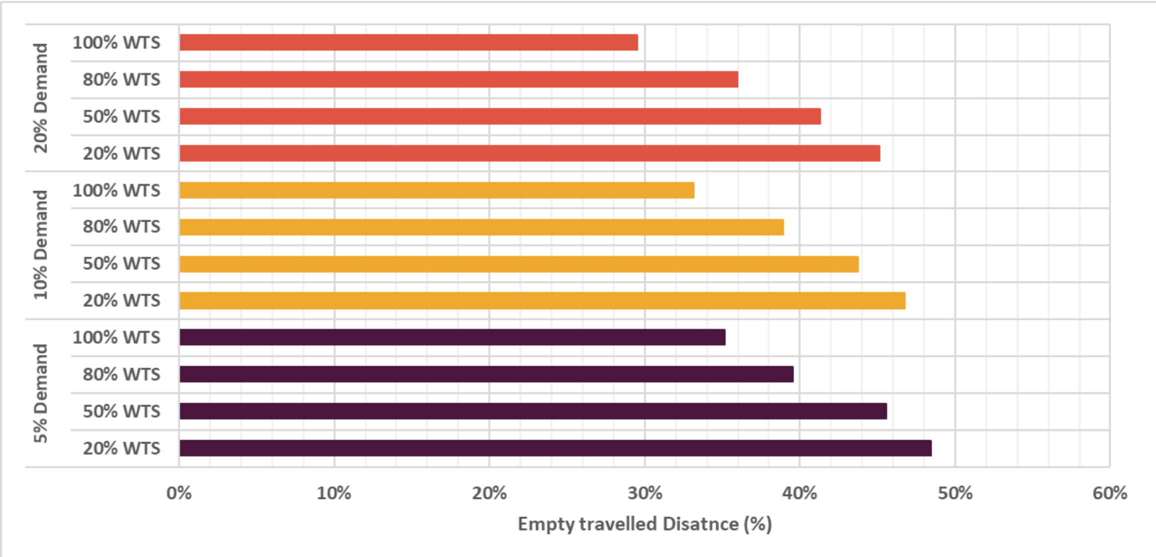


Figure 3.14: Percentage of empty distance travelled by the entire SAV fleet

3.1.2.5 Green Light Optimal Speed Advisory (GLOSA)

The traffic microsimulation model that is used for this sub-use case was provided by Transport for Greater Manchester. The model of Greater Manchester provides a sufficiently large and complex transport network with signalized intersections and other various road sections, rendering it suitable for the specific experiment. For implementing GLOSA, a corridor near the Salford area (Figure 3.15) was selected in Manchester with three signalized intersections sufficiently distant from each other. The impact of GLOSA was analysed under fixed time coordinated traffic control at these study locations.

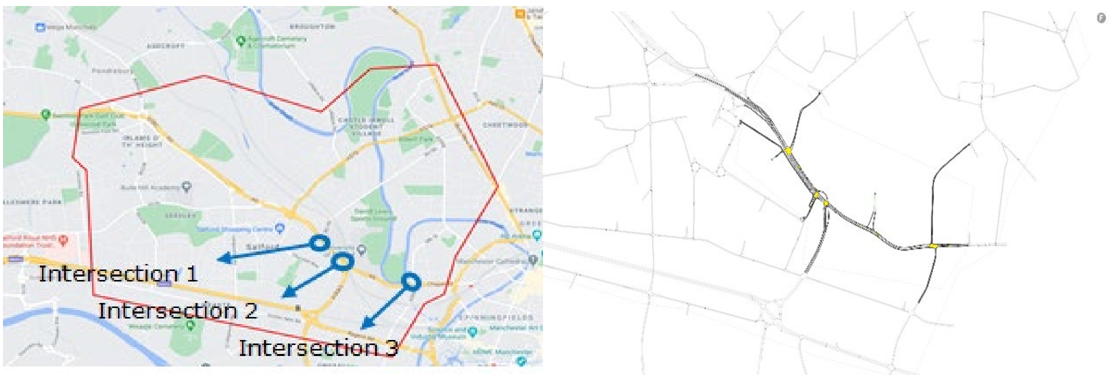


Figure 3.15: Test corridor in Manchester network for GLOSA application

The test scenarios on GLOSA implementation and CAV deployment are as follows:

- Baseline scenario – No GLOSA, CAV market penetration from 0% to 100% in 20% increments,
- Scenario 1 – GLOSA on intersection 1,
- Scenario 2 – GLOSA on intersections 1 and 2,

- Scenario 3 – GLOSA on intersection 1, 2 and, 3.

Simulations were performed for the peak hours on baseline and all three analysis scenarios with CAV deployment as shown in Table 3.2.

The following assumptions were made in the frame of GLOSA application:

1) The quality of communication between signals and vehicles is ideal and all messages are delivered successfully and without delay,
2) All the drivers accept and comply with the recommended speed,
3) GLOSA is applied at each simulation step,
4) All CAVs will have the capability to communicate with traffic controllers,

Simulations were run for the peak hours performing 10 replications under each scenario.

GLOSA Algorithm

GLOSA Algorithm was developed based on reviewing some of the previously developed algorithms in literature (Stevanovic et al, 2013) with modifications as deemed adequate for the test network. The key steps describing the functionality are presented in Table 3.5.

Table 3.5: Steps involved in GLOSA system operation

Step 1. GLOSA system in vehicle searches for a traffic signal controller downstream **Step 2.** If a traffic signal controller downstream is detected, go to step 3, else go to step 1 **Step 3.** GLOSA system in vehicle collects data on vehicle position and speed **Step 4.** Get Map Data Message (MAP) information about the lane and turning restrictions. (GLOSA application generates geometry from MAP message to determine the vehicular position and determine the corresponding lane number) **Step 5.** Calculate vehicle's distance to stop bar at the intersection approach **Step 6**. Determine the existing queue length at the current moment **Step 7**. Collect current signal phase and timing information (SPAT) from the controller at the current moment for corresponding lane of the approach at the intersection. **Step 8.** Calculate the time required to arrive at the intersection **Step 9.** Determine the phase at the arrival time -If the current phase is Green, check if vehicle is arriving at Green? If yes, go to step 10, If not go to step 11. -If the current phase is Red check if vehicle is arriving at Green. If yes, go to step 10, if not go to step 14. **Step 10.** Vehicle is arriving at Green. Send advisory message to maintain current speed **Step 11.** Vehicle is not arriving at green. Calculate advisory speed to arrive at current green phase **Step 12.** Is advisory speed ≤ speedMax and advisory speed ≥speed Min, If yes go to step 13, else go to step 14 **Step 13.** speed up to advisory speed **Step 14.** Calculate the advisory speed to arrive at junction on next green phase by using current queue length and queue dissipation time. **Step 15.** If the advisory speed ≥speed Min and advisory speed ≤ speedMax (where speedMin=50% speed limit), If yes go to step 16, else go to step 17 **Step 16.** Slow down to speedMin **Step 17.** Exit (vehicle will have to stop)

Before applying the GLOSA algorithm on the test network, the impact of activation distance and frequency of GLOSA was analysed. The activation distance was kept to 400m while GLOSA was applied on each time step. Minimum speed threshold was kept as 50% of speed limit as also used in several other studies (Katsaros et al.,2011, Masera et al.,2019) while upper limit was kept as speed limit +5mph.

3.2 Mesoscopic simulation of activity chains

The mesoscopic mobility simulation of agents and their plans of activities is used as a method to estimate the medium-term consequences of RUP on several defined impacts and the short-term impact of travel time described in Deliverable D6.2 (Haouari et al., 2021). The model is based on calibrated choice behaviours of the simulated population, and its methods provide the means to draw direct, data-supported conclusions on the altered choices of agents regarding the use of transport modes under changing circumstances of transportation availability. The intent of implementing RUP for a chosen area is regional reduction of use of the tolled modes of transport, which, in the presented scenarios are the conventional and automated passenger cars. Due to the nature of the employed mesoscopic simulation models – both in terms of pricing scope and granularity – the following impacts studied within the project can be expected to indicate significant medium-term consequences for different road pricing schemes: The amount of travel (section 4.2.1), the modal split using public transport (section 4.3.1) and the modal split using active transport (section 4.4.1). Reduction in the use of tolled modes impacts the overall characteristics of the changed population of mobile agents (representing traveling persons within the simulated area) and their trips between locations of activity.

All investigated scenarios were developed for a model of Vienna and its wider surrounding area shown in Figure 3.16 to serve as a prototypical example for a historically grown ("old" European) city. The segmentation of the city into roughly ring-shaped domains that lie concentric around the city centre was made to enable analyses in accord with the defined impact requirements. Borders between these domains are formed by major arterial (ring-) roads which are used to circumvent crossing through more densely populated areas towards the city centre.

Each agent within the mesoscopic simulation uses a decision model, which is based on the best available statistical knowledge of such an agent's characteristics regarding geographical locations, daily activity patterns and sociodemographic variables. Being a central component of the activity chain simulation model, it allows individual agents to react to changes in model conditions by adapting their daily activity plans and utilized modes of transportation. Adaptions are gauged with respect to their "goodness" by using a *utility function* that summarizes the timeliness of activities reached as well as how costly it was to access those places of activity considering both time and money. The attributed weights of these last two cost factors are described by the parameters "value of travel time saved" (VTTS) and "marginal utility of money" (mUoM), respectively. On the one hand, a dominating high value of VTTS for a specific agent will result in behaviour that tries to greatly reduce the time-costs of traveling. A dominating high value of mUoM on the other hand will encourage behaviour that strives for monetary cost reduction.

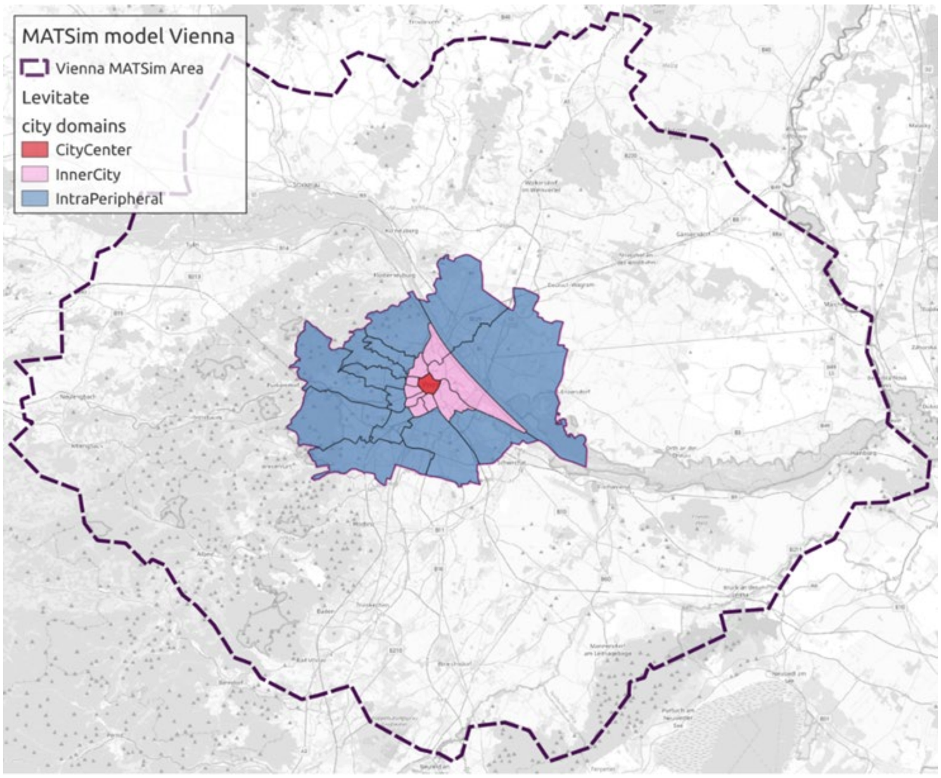


Figure 3.16: MATSim model Vienna total area overview. The color-shaded domains within the model area cover the actual extent of the city of Vienna. The dashed line marks the wider model region surrounding the city.

A major assumption of the employed model is that such domain structures can be defined for most cities with a comparable structure and evolution.

The four defined domains are:

1. **City centre (CC)**: mostly reduced vehicle traffic areas, restricted entry is common,
2. **Inner city (IC)**: containing a densely populated belt around CC with lots of habitation areas,
3. **Intra peripheral (IP)**: domain outwards from IC up to the city limits which enclose the actual investigation area; habitation regions, some commercial, light industrial areas, larger recreational zones,
4. **Extra peripheral (XP)**: the remainder of the model area, defining the outer boundary and conditions for the inner investigation area.

3.2.1 Model description

The **mesoscopic MATSim simulation model for Vienna** is described in detail in (Müller et al., 2021). In short, the simulation area (see Figure 3.16) covers about 4,100 square kilometres with a population of about 2.3 million including the 1.7 million inhabitants of Vienna (Eurostat, 2019). We used a 12.5% sample of the mobile population which corresponds to around 200,000 agents in the whole simulation area. By simulating traffic in the vicinity of at minimum 30 kilometres from the city centre, large parts of the Vienna metropolitan area are covered. The road network for the simulations comprises of 156,000 links, and various facilities like workplaces, schools, shopping, and leisure areas.

MATSim requires an initial set of travel diaries of the agent plans representing a set of activity locations for a given sequence of activities. These parameters do not change over simulation iterations and in the scenario simulations. To simulate traffic on the road network, two main data sources are utilized. The first is travel diaries with detailed origin-destination matrices, choice of transport mode, and various socioeconomic indicators of the surveyed mobile population. This information is provided by the Austrian national mobility survey "Österreich Unterwegs 2013-2014" (Tomschy et al., 2016) which is representative at the municipality level throughout the modelled region. The second input dataset is the locations of facilities or points of interest extracted from OpenStreetMap. They are used to provide distinct activity locations (facilities) by disaggregating the available coarse spatial information of municipality. This is done for travel origins and destinations and is categorised by housing, work, education, shopping, recreation, and errands. These data are supplemented with population density maps derived from (Eurostat, 2019) to spatially map the facilities along with the potential places of residence and work for the simulated agents.

Thus, disaggregating the activity location survey information means selecting appropriate points of interest from the specified community area code. This selection is done by applying an optimization algorithm based on the travel times and travel distances specified in the travel survey data. As a result, we obtain optimal matching locations for each agent's activity sequence within the set of possible locations for each activity type.

After the synthetic population is generated, these plans are fed into an inter-modal routing algorithm to generate several likely paths a trip will take. This is done using Austrian Institute of Technology's (AIT) proprietary inter-modal routing algorithm *Ariadne* (Prandtstetter, Straub & Puchinger, 2013)

MATSim works with a scoring function to evaluate the success of an agent's travel diary at the end of the day. The basic logic behind this utility function is to reward times spent at a planned activity location and penalize all travel times according to the mode. The scoring parameters for each mode are estimated from a stated and revealed preference survey (Hössinger, et al., 2020; Jokubauskaite et al., 2019). The model is calibrated by the modal split for each trip according to the travel diaries given in the "Österreich Unterwegs 2013-2014" survey. After adjusting the constant of the mode utility functions, a deviation from the observed data of less than 1% for each mode was achieved.

Consistent with overall project goals to describe likely automation scenarios of the future, the of different car fleet partitions of CAV of the 1st generation ("cautious" CAV1) and CAV of the 2nd generation ("aggressive" CAV2) is indicated in Table 3.6. The vehicles' characteristics are represented in the model by assigning different utility functions (see section 3.2) for private cars to randomly distribute shares of the population. For a definition of these generations also see section 3.1.1. Using an AV1 will therefore be attributed with 80% of the VTTS of a private car, while an AV2 with 75% of a car's VTTS, which accounts for the possibility of the attention or time in the vehicles to be spent on other things but driving. The rationale behind setting the parameters for CAV1, CAV2 is based on studies on the estimation of the VTTS for automated vehicles and shuttles. Whereas Lu et al. (2018) found no differences in the VTTS between drivers and passengers of a car, Fosgerau (2019) and Ho et al. (2015) come to the conclusion that the VTTS for a passenger can be regarded as about 75 % of the rate for car drivers. We follow in our model these latter findings and slightly increase the VTTS for CAV1 as the driving experience is assumed to be not as convenient as with a CAV2.

As the throughput of roads will increase with a higher automation rate due to more densely packed moving vehicles, the simulation model parameter "flow capacity factor" of the road network was adapted to account for this effect. The flow capacity factor is generally set to the percentage of the population that is simulated (in our case 12.5%) as it represents the relative number of vehicles that can pass a link (Llorca & Moeckel, 2019). This was done in accordance with earlier project results on the passenger car unit (PCU) dependency obtained by microscopic simulations (Tympakianaki, Nogue, Casas, & Brackstone, 2020) and is also shown in Table 3.6. The private cars' behaviour will remain the same in any other respect.

In addition, three different scenarios of the economic situation of agents are considered by variation of the marginal utility of money (mUoM), which was either left at the baseline settings (no economic change) or set to an increase/decrease of 5% resembling correlation to the ratio of inflation rate by average available income.

For each of the common eight different car fleet partitions of CV, AV1 and AV2, every combination of RUP implementation and the marginal utility of money was simulated.

Table 3.6 The CAV market penetration rate scenarios and the respective shares of AV generations and the anticipated increasing road network throughputs given as flow-capacity-rate.

Type of Vehicle	**A**	**B**	**C**	**D**	**E**	**H**	**F**	**G**
Conventional Car	100%	80%	60%	40%	20%	0%	0%	0%
1st Generation CAV	0%	20%	40%	40%	40%	0%	40%	20%
2nd Generation CAV	0%	0%	0%	20%	40%	100%	60%	80%
Flow capacity rate	0.1150	0.1205	0.1262	0.1317	0.1368	0.1413		

3.2.2 Implementation assumptions

A simplified schematic view of the full model region (as in Figure 3.16) is depicted in Figure 3.17. The investigation area is defined as inside the city limits (everything including domain intra-peripheral and inwards) which is delineated by the investigation perimeter.

As was defined in the project goals, the relevant area for implementing RUP scenarios should comprise everything within IC (i.e., tolling should happen on crossing into or traveling within IC).

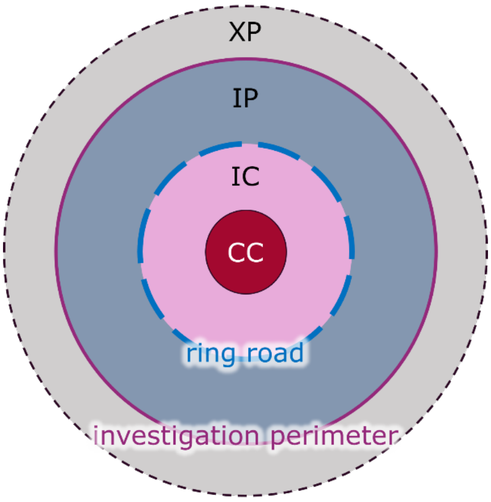


Figure 3.17 Schematic view of the four city domains used for mobility investigations. The domains are city centre (CC), inner city (IC), intra peripheral (IP) and extra peripheral (XP).

To analyse the implementation measure of RUP, deployment of automated passenger cars considers each vehicle as a privately owned car. These vehicles are not capable to relocate or carry out rides on their own, thus providing autonomy and driving capabilities only when the owner is aboard.

The indicators derivable from the developed scenarios as specified within the project are:

- travel time of an average 5 km trip within the inner city,
- modal splits and modal shifts (i.e., changes in modal split) of active (walking or cycling) and public transport modes of travel,
- total distance travelled within the city.

Regarding the definition of these indicators, some details need to be given:

- The modes available in the simulation model to sufficiently describe the diverse travel activities are car (conventional), AV1 (automated car "cautious"), AV2 (automated car "aggressive"), PT (public transport), bike (cycling), walk. To consider the main transport mode of a trip, the longest-distance-mode (ldm) of any given locomotion between two places of agent activity was chosen, with these activities resembling the fixed intermediary stops along a daily plan or journey.
- The travel time was defined for trips within the tolled area (IC), as an inverse speed of minutes per 5 km distance (1/5 [min / km]). Additionally, an upper quantile of 0,15 % of the inverse speed for each of the separate modes of transport was removed to reduce the influence of outliers (that took unreasonably long to complete their trips) on the mean-value statistics, therefore improving statistical robustness of the travel time indicator.
- The total distance travelled was defined as the sum over all those parts of any trip that lie within the limits of the whole city.

3.2.3 Scenarios

Static RUP

Definition: The term static toll refers to the payment of a fixed amount due whenever a vehicle enters a defined tolling area. For the presented SUC this means that no distinction is made regarding the type of passenger car, thus including conventional vehicles (CV), "cautious" automated vehicles (AV1) and "aggressive" automated vehicles (AV2).

The tolling fees were implemented in several pricing levels with corresponding rationales:

- 0 €: resembling unimplemented policy,
- 5 €: as moderate policy level of discernible effects,
- 10 €: as elevated policy level of larger effects,
- 100 €: as "full-force" prohibitive policy level, exerting the maximum policy effect expectable.

Dynamic RUP

Definition: The term dynamic toll refers to the payment of a fixed amount due for each unit of distance (i.e., 1 [km]) a vehicle travels within a defined tolling area. For the presented SUC this means that no distinction is made regarding the type of passenger car, thus including conventional vehicles (CV), "cautious" automated vehicles (AV1) and "aggressive" automated vehicles (AV2).

In accordance with the SUC of static RUP, the dynamic tolling fees per unit distance were chosen comparably for the IC area, where the approximate diameter of this area is set to 7 km. In the dynamic RUP tolling scheme, the full crossing of the diameter distance of 7 km results in the same tolling fee levels as given for the static RUP. Presupposing equivalent intentions regarding the implementation of measures, tolling fees therefore calculate to 0, 5/7, 10/7 and 100/7 [€/km], respectively.

3.3 System dynamics

System dynamics (SD) is a mathematical modelling technique which can be used to understand the dynamic (nonlinear) behaviour of complex systems over time using stocks, flows, feedback loops, table functions and time delays. In modelling terms, systems dynamics models are continuous simulation models in which a system may be represented as a causal loop or stock flow diagram. The relationships between different variables can be expressed as general quantitative forms. Those variables which are interrelated connect through feedback loops which respond to the system conditions. This modelling approach provides the flexibility to modellers to add a larger number of parameters or influencing factors in the model compared with other conventional methods.

System Dynamics in LEVITATE is used as a supplementary approach, in order to investigate several longer-term impacts which cannot be covered by other methods: the modal split (for use of public transport as well as active modes) that will be covered in this Deliverable, the demand for public parking space and the (average) commuting distance.

In the following sub-section, a summary of the used base model – across all SUC – is given, followed by detailed information on the data used, the definition of zones and the calibration of the model. Finally, the implementation of the WP6 specific sub-use case in the system dynamics model is described.

3.3.1 Description of the base model

The basic system dynamics model used in LEVITATE can be considered as three sub-models which are interacting with each other, as depicted in Figure 3.18:

- At the core, the Transport Model is modelling the *travel demand and trips* (based on segmentation of the target area into geographical zones and the mode of transport). Both the change of total demand and the shift between several modes are influenced by the generalized costs. *Total modal split* is the most important impact variable calculated in this model.
- In order to generate and drive the demand, a precise *population* model has been implemented (segmentation into age groups, zone and income groups). Further this model is used to calculate the *average commuting distance* impact variable.
- Finally, the use of *public space* is modelled on zone level, distinguishing between parking space, driving lanes and other purposes. The *relative demand for parking space* is calculated in this model.

The generalized costs for travelling are composed by four influencing variables in the following way:

$$\mathit{Generalized\ Costs} = \mathit{Travel\ Costs} + (\mathit{Travel\ Time}) * (\mathit{Value\ of\ Travel\ Time}) - \mathit{Attractiveness}$$

Obviously, lower generalized costs might result from changes in any of these four variables, and lead to an increase in corresponding trips. Such changes in the model are caused by:

a) Increasing AV penetration rate – the variable considered as the main parameter in LEVITATE to investigate the development over time,
b) Specific sub-use cases (SUC) considered on top of increasing AV penetration rate.

Despite the simplicity of the described model, certain impacts can be assessed in a quantitative way, due to following features of the model:

- The system exhibits multiple (balancing) *feedback loops*, both within the sub-models and between them: Higher share of private car trips, for example, will increase the relative demand for parking space in an area, leading to higher parking search time and consequently higher generalized costs which, resulting in decreasing demand.
- While on high level of aggregation compared to micro-simulation and mesoscopic simulation approaches, the model is segmented with respect to geographic zones, age and income groups. This allows for calculation of much more specific dependencies than considering only the average (aggregated) values of all system variables.
- Finally, the model has been fed with data to calibrate the system against the current behaviour (i.e., the case of no automation), showing the observed modal split values (for the case of Vienna) – this is explained in more detail in the next section.

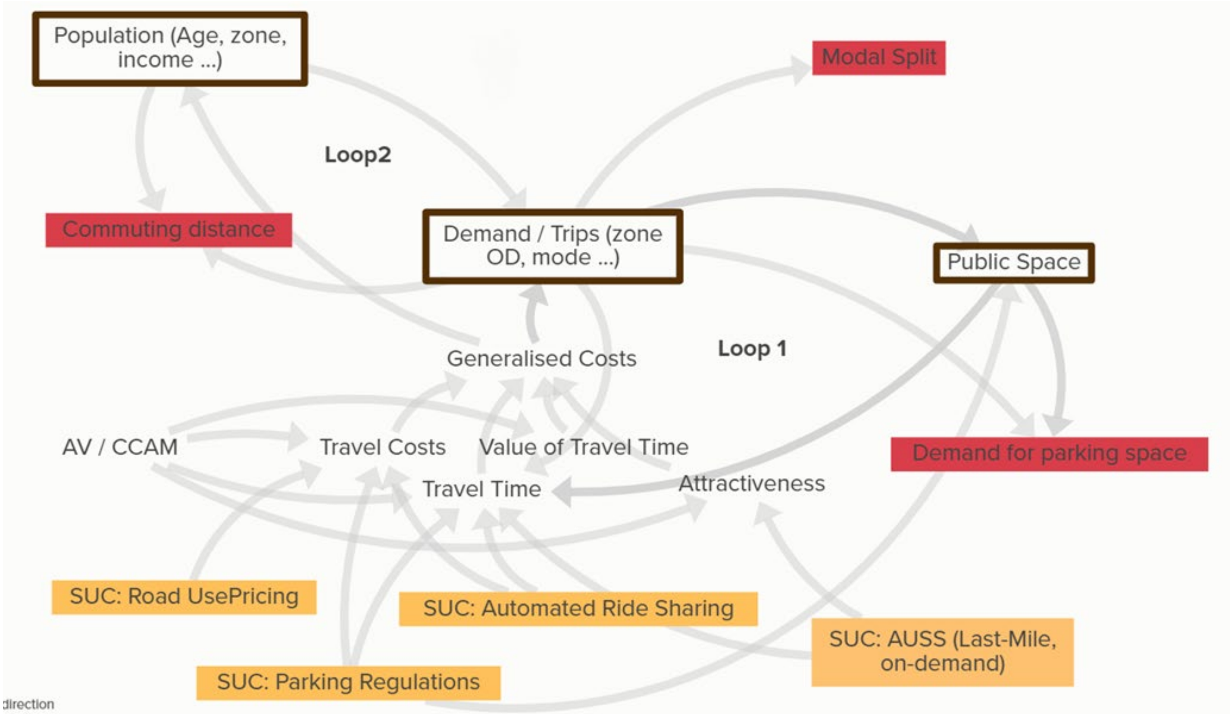


Figure 3.18: High level overview of the LEVITATE System Dynamics Model, showing main submodules (boxes), calculated impact variables (red) and implemented sub-use cases (yellow)

In order to document the assumed dependencies between variables in full detail, the Vensim.[1] views for the main submodules are shown in Figure 3.19 -Figure 3.21.

[1] Vensim from Ventana Systems (https://vensim.com) is the tool that has been used to implement the SD model.

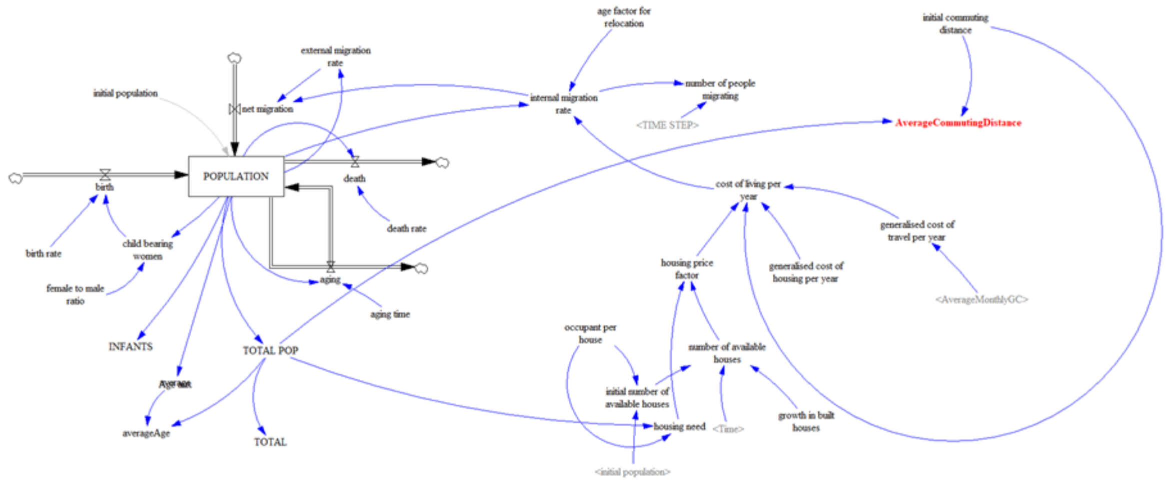


Figure 3.19: Detailed Vensim view of the population model

These diagrams also show which of the key variables have been modelled as stock variables – which are essential for implementing a quantitative system dynamics model that can be simulated:

- The *population*, using the subscripts Age and Zone,
- The number of *trips* as central model variable, using the subscripts Age, Origin Zone, Destination Zone and Mode,
- Three forms of available *Public Space* – parking space, lane space and multi-functional / active modes – using the subscript Zone.

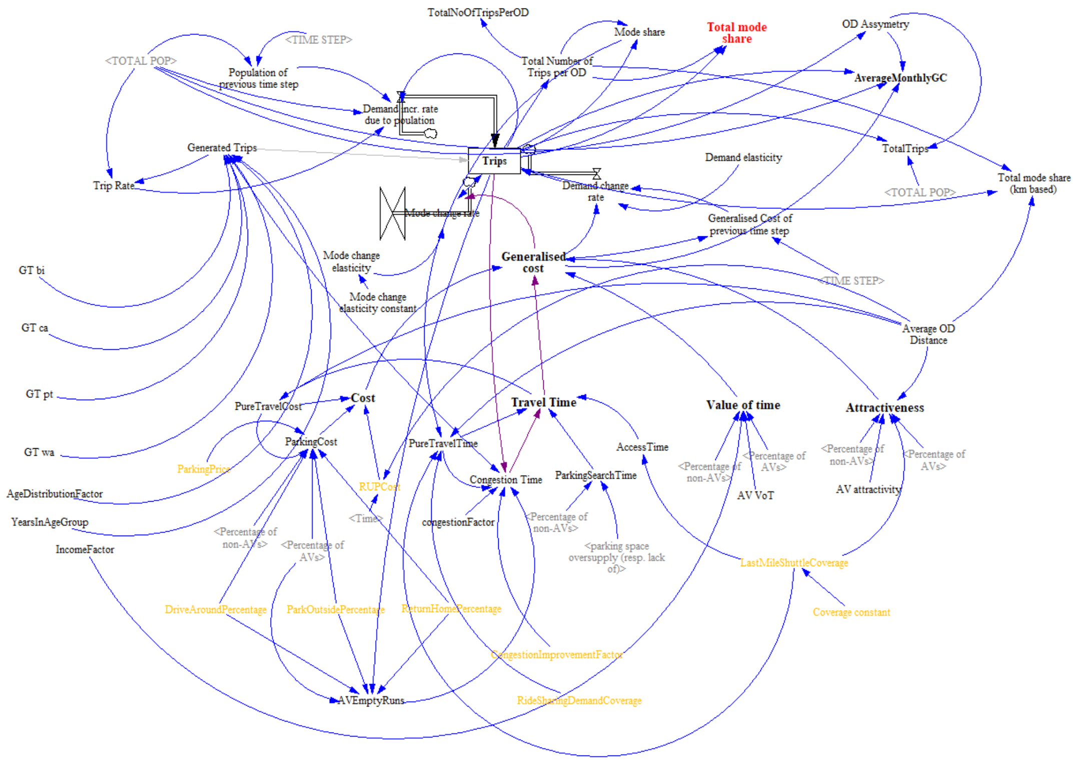


Figure 3.20: Detailed Vensim view of the transport model (Demand / Trips)

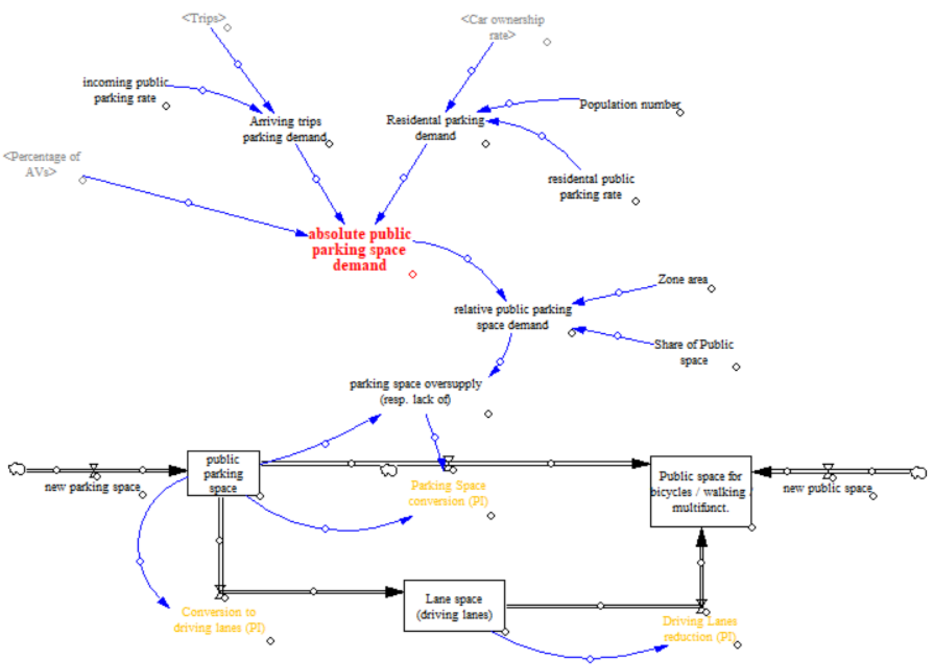


Figure 3.21: Detailed Vensim view of the public space model

3.3.2 Model data, zones, and calibration

The SUC scenarios were investigated in a SD model that is sharing the basic data on population, area, and trips with the MATSim model of Vienna, introduced in Deliverables D5.2 and D6.2. This model has been used for calibrating the SD model (providing the correct population structure, modal split etc.). Therefore, the SD model also covers Vienna and its wider surrounding area as shown in Figure 3.16, serving as a prototypical example for a historically grown ("old" European) city. The area is segmented into roughly ring-shaped domains that lie concentric around the city centre. Borders between these domains are formed by major arterial (ring-)roads which are used to circumvent crossing through more densely populated areas towards the city centre.

A major assumption of the employed model is that such domain structures can be defined for most cities with a comparable structure and evolution. The four defined domains have been described in section 3.3.

The calibrated system dynamics model in the absence of automation (AV penetration rate = 0) and any SUC / interventions (No Automation baseline) is very close to an equilibrium; the calculated impact variables stay constant over time and represent the current values.

3.3.3 Implementation of SUCs

In WP6, system dynamics has been used to cover following SUCs:

- Road Use Pricing (RUP),
- Parking Price policies,
- Parking space regulations,
- Automated Ride Sharing.

The integration of these SUCs into the SD model is highlighted in Figure 3.22. More precisely, the SUC related input parameters are based on assumptions as well as outputs from the microscopic simulation as specified in Table 3.7 below.

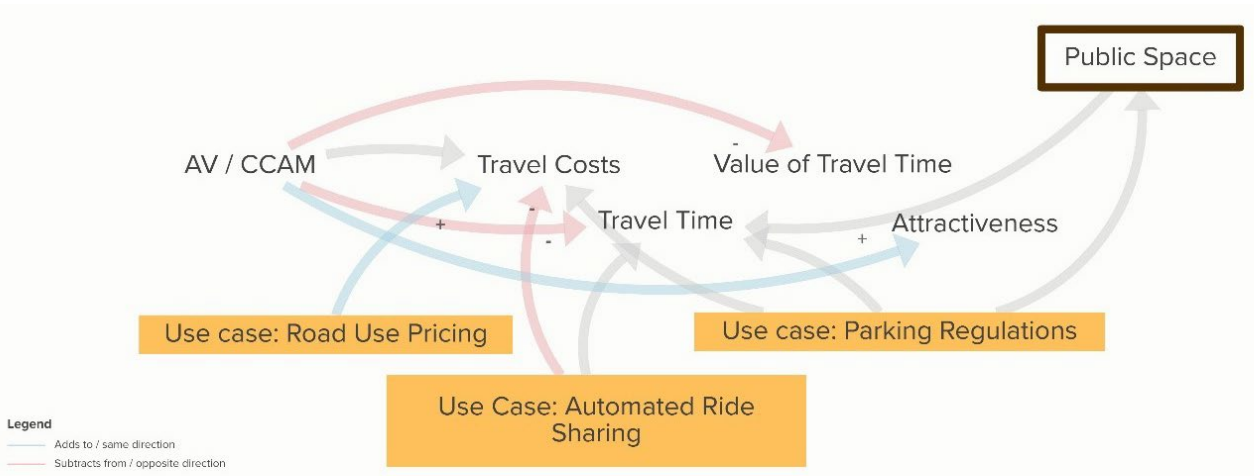


Figure 3.22: Implementation of WP6 SUCs in the SD model (red arrows reflect negative polarity, blue arrows positive polarity, and grey arrows unspecified polarity)

Table 3.7 SUC related input parameters in SD model

SUC	Road Use Pricing	Parking Price policies	Parking space regulations	Automated Ride Sharing
SD parameters (explicitly modelled)	Static toll (10 EUR) Toll area: zone 1 and 2	Average parking fee (5 EUR for balanced behaviour)	% reduction of public parking space (50%) in zone ½	Percentage of passenger car demand served (20%) Willingness to share (100%)
Implicit inputs (microsim results)	(None)	% driving around % parking outside % returning home	Changes in travel time/delay	Changes in travel time/delay

3.4 Delphi

3.4.1 Background of the Delphi method

The Delphi method is a process used to arrive at a collective, aggregate group opinion or decision by surveying a panel of experts. This concept was developed by the RAND Corporation for the military in order to forecast the effects of new military technology on the future of warfare, and then continued to make multiple practical applications of this method (Dalkey & Helmer, 1963). The Delphi methodology is based on a repetitive interview process in which the respondent can review his or her initial answers and thus change the overall information on each topic (Hsu & Sandford, 2007). This presupposes that the participants will be willing to not only give answers on the topics but also to repeat the interview in possibly more than two cycles. The Delphi method has three different dimensions: the exploratory Delphi aiming at the forecast of future events, the normative Delphi, in order to achieve policy consensus on goals and objectives within organisations or groups and the focus Delphi in order to gain feedback from stakeholders in some policy outcome (Garson, 2012). The Delphi method presents the following characteristics and features: the anonymity of experts which assures free expression of opinions provided by the experts. This method helps to avoid social pressure from dominant or dogmatic individuals or even from the majority or minorities. At any point, experts can change their opinions or judgments without fear of being exposed to public criticism, providing controlled feedback as experts are informed about the views of other experts who participate in the study (Profilidis & Botzoris, 2018).

3.4.2 The Delphi method within LEVITATE

Within LEVITATE, the Delphi method is used to determine all those impacts that cannot be defined by the other aforementioned quantitative methods (traffic simulation, system dynamics, etc.). Initially, a long list of experts was identified for each use case (i.e., urban transport, passenger cars and freight transport), and contacted via an introductory mail asking them to express the willingness of participation. Those who responded positively participated in the main Delphi process, amounting to 70 experts in total. (5 experts accepted to answer to 2 questionnaires). Experts come from various organisations such as research institutes, companies and universities (presented in Figure 3.23) where they have different job positions, such as directors, professors and managers (presented in Figure 3.24) and they come from different countries (presented in Figure 3.25).

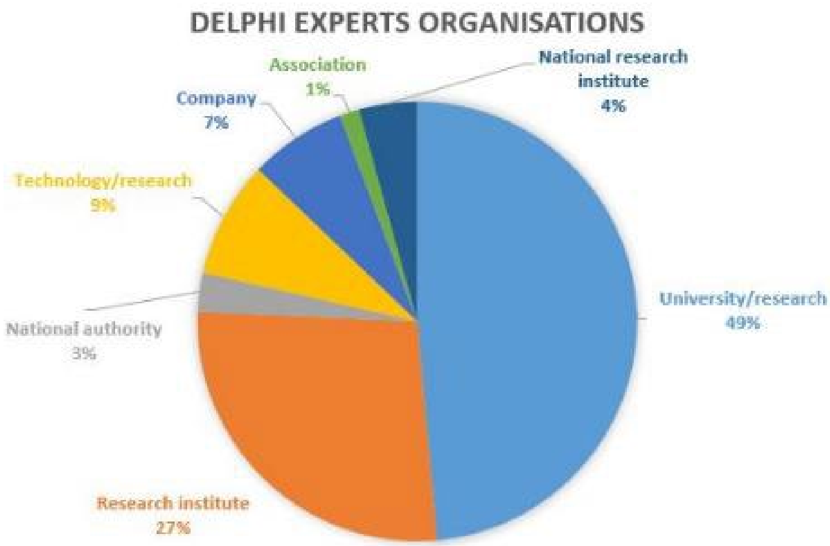


Figure 3.23: Delphi experts' organisations

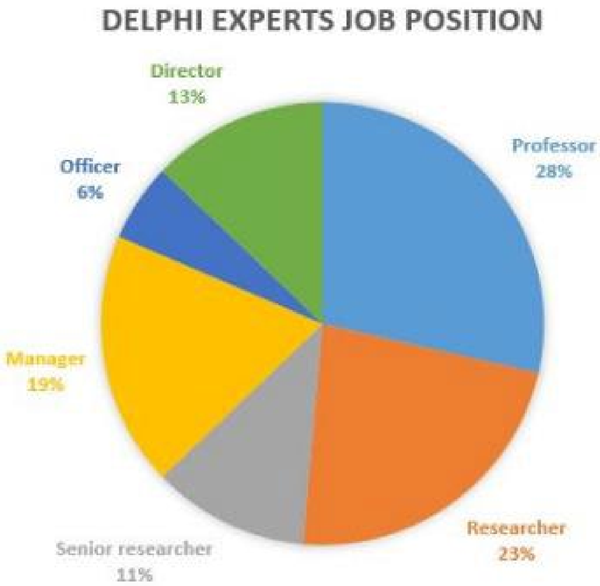


Figure 3.24: Delphi experts' job positions

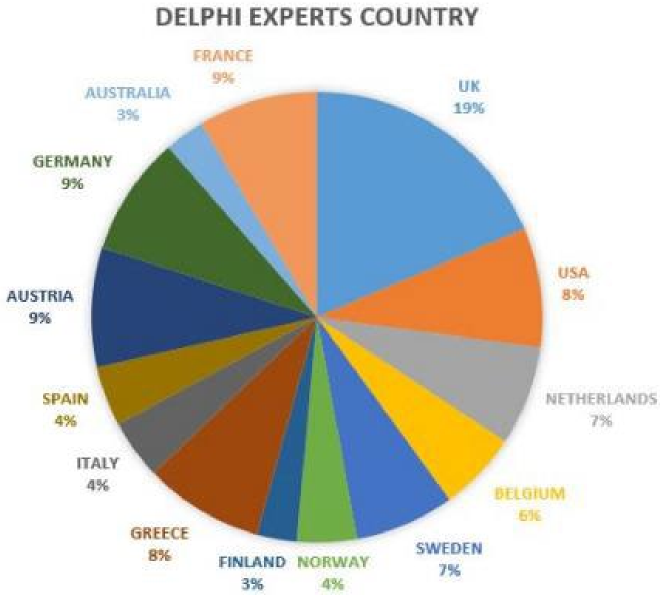


Figure 3.25: Delphi experts' countries

The Delphi method consisted of two rounds of e-mails. During the first round, experts received a questionnaire (30-45min duration) regarding a few (2-4) automation interventions related to automated urban transport, automated passenger cars or automated freight transport, as per their specific expertise. Before starting the questionnaire, they were asked to reply to the consent form accepting the use of the information they will add in the questionnaire. Then they were asked to evaluate the potential influence of the proposed interventions on different impact areas. Their answers were then analysed in order to create (anonymous) summary data for the different CCAM related interventions. These results were distributed with the second-round questionnaire and gave respondents the opportunity to reflect on the first-round outcomes before providing their answers again. In some cases, it led to respondents changing their first-round responses to something conforming more to the answers provided by other respondents.

In each first round questionnaire, experts were asked about the influence of automation related interventions on the proposed impacts for different connected & automated vehicle (CAV) market penetration rates. The CAV market penetration rates used are 0% (the baseline scenario), 20%, 40%, 60%, 80% and 100%, as defined by micro-simulation scenarios at the corresponding stage in the project; all methods have been using the same scenarios to achieve uniformity of the different results. The impacts included in the Delphi method are: travel time, vehicle operating cost, amount of travel, access to travel, modal split of travel using public transport, modal split of travel using active travel, shared mobility rate, vehicle utilization rate, vehicle occupancy, parking space, energy efficiency, public health and inequality in transport.

For each impact and each automation related scenario the participants were asked to indicate the percentage of change that the intervention would have for the mentioned CAV market penetration rates (Figure 3.26). The percentages varied from -100% to +100% where the negative (minus sign) was either an improvement or a deterioration depending on the type of impact. For example, a negative effect on travel time would mean a reduction and thus an improvement, while on the other hand a negative percentage of change on public health would mean a deterioration.

1. In your opinion how will the introduction of AVs affect travel time? *

Mark only one oval per row.

	-100% to -70%	-69% to -40%	-39% to -20%	-19% to 0%	0% to 20%	21% to 40%	41% to 70%	71% to 100%
for AV penetration rate 20%								
for AV penetration rate 40%								
for AV penetration rate 60%								
for AV penetration rate 80%								
for AV penetration rate 100%								

Figure 3.26: Example of Delphi questions

Participants were divided in seven groups. Each group had a different questionnaire related to a specific type of interventions based on their expertise. Each questionnaire concerned 2-4 automation related interventions, including the baseline scenario where no policy intervention is applied except the introduction of CAVs in the urban environment. The questionnaire was also separated with size limitations in mind, as passenger cars would constitute an immense single questionnaire if their sub-use cases were considered all at once. For LEVITATE WP6:

- 10 experts participated in the first Delphi round for the parking regulations sub-use cases and 5 continued to the 2nd round.
- 10 experts participated in the 1st Delphi round for the parking behaviours sub-use cases and 6 continued to the 2nd round.
- 10 experts participated in the 1st Delphi round for the ridesharing and GLOSA sub-use cases and 6 continued to the 2nd round.

- 10 experts participated in the 1st Delphi round for the AV dedicated lanes sub-use cases and 6 continued to the 2nd round.
- 10 experts participated in the 1st Delphi round for the city toll sub-use cases and 7 continued to the 2nd round.

After the reception of the answers of the 1st Delphi round questionnaires, subsequent aggregation coding and analysis followed. For each intervention and each impact, a table was created: its rows represented the CAVs market penetration rates and the columns the different percentages of change (Table 3.8). All experts' answers were introduced in the table and then for each row (each CAVs market penetration rate) the percentage equal with the average of all answers was extracted.

Table 3.8: Example 1st round Delphi answers analysis

Centroids	-85%	-55%	-30%	-10%	10%	30%	55%	85%
AV MPR	-100% to -70%	-69% to -40%	-39% to -20%	-19% to 0%	0% to 20%	21% to 40%	41% to 70%	71% to 100%
20%	0	0	1	3	6	4	0	0
40%	0	0	0	3	6	2	3	0
60%	0	0	1	3	3	6	1	1
80%	0	0	3	4	1	2	4	0
100%	0	2	4	1	4	0	2	0

This percentage is the coefficient that will be used in the PST (Table 3.9). The conversion to percentage fluctuations ensures that the PST operates with different starting values provided either by default or by the user, to increase the flexibility and applicability of the tool.

Table 3.9: Example table PST coefficients

AV MPR	Aggregate change	PST coefficients
20%	2.75%	1.028
40%	-1.50%	0.985
60%	19.68%	1.197
80%	32.61%	1.326
100%	35.43%	1.354

Additionally, for each impact, a curve was created representing the values of the percentages for the different CAV market penetration rates. The resulting curves for all interventions and impacts were presented to the experts for the 2nd round of the Delphi, who were then asked whether they agreed with the 1st round results (Figure 3.27). They were given the opportunity to propose different percentages in case they disagreed. These suggestions were then incorporated in the final coefficients introduced in the LEVITATE PST through a weighted average scheme to make sure that each expert contributes equally.

Do the resulted curves look relevant to your vision of the future? *

	Definitely	Moderately	Slightly	Not at all
Baseline scenario	○	○	○	○
Point to point AUSS	○	○	○	○
Anywhere to anywhere AUSS	○	○	○	○
Last-mile AUSS	○	○	○	○
E-hailing	○	○	○	○

Figure 3.27: Example of round 2 questions

4 Medium-term impacts

In order to provide a structure to assist in understanding how CCAM impacts will emerge in the short, medium and long-term, a preliminary taxonomy of the potential impacts of CATS was developed by Elvik et al. (2019). This process involved identifying an extensive range of potential impacts which may occur from the future expansion of CCAM. A range of impacts were classified into three categories, direct impacts, systemic impacts, and wider impacts. Systemic impacts are impacts wide enough to be observed across the entirety of the transport system. These are measured independently from direct impacts and are considered medium-term.

This part of the deliverable presents description and quantification of the medium-term impacts of automated passenger transport. In this regard, seven key impacts have been analysed under each sub-use case using an appropriate methodology as described under section 3. They are as follows:

1. **Congestion,**
2. **Amount of travel,**
3. **Modal split of travel using public transport,**
4. **Modal split of travel using active travel,**
5. **Shared mobility rate,**
6. **Vehicle utilisation rate,**
7. **Vehicle occupancy.**

This section is organized based on the above listed medium-term impacts, and under each impact type, results from each sub-use case intervention have been presented and discussed. An overview of the methods used to estimate these impacts in this deliverable is present in Table 4.1.

Table 4.1: Overview of the methods used to estimate medium-term impacts of connected and automated vehicles under WP6

Impacts	Methods			
	Microscopic Simulation	Mesoscopic Simulation	System Dynamics	Delphi
Congestion	✓			
Amount of travel	✓	✓		✓
Modal split of travel using public transport		✓	✓	✓
Modal split of travel using active travel		✓	✓	✓
Shared mobility rate				✓
Vehicle utilisation rate)				✓
Vehicle occupancy				✓

4.1 Congestion

Within LEVITATE, quantification of the impact of congestion for CAVs with various SUCs was conducted by using the microsimulation method. In terms of microsimulation approach, the microsimulation result of average delay (measured in sec/km) has been chosen as the key KPI for estimating the impact of congestion. It should be noted that the baseline trends could be varied between the different sub-use cases since several networks with various characteristics were used across the project.

4.1.1 Provision of dedicated lanes on urban highways

Under baseline scenario, the results show some irregular trend with respect to delays showing delays under scenarios with increased automation of 1st as well as 2nd generation vehicles (Figure 4.1). This is primarily due to the assumptions used to model CAVs behaviours.

With the provision of CAV dedicated lane, the results showed minimum delays in case of A-road innermost lane placement scenario. The fluctuations in trend under all scenarios could be attributed to the reason that dedicating a lane of CAVs, initially or at Low MPRs the predominant part of the impact on traffic will be on non-dedicated lanes, while at higher MPRs, the traffic flow on CAV dedicated lane can be negatively affected, consequently increasing overall delays in the network. This indicates potential disbenefits under low and high MPR scenarios with one dedicated CAV lane. However, under higher MPR scenarios, two dedicated lanes can improve the traffic performance.

With regard to MPR of AVs, the results indicated relatively less delays at moderate penetration rates scenario such as indicated in Figure 4.1 at 60-40-0, particularly under A road scenarios. These findings are also in line with those reported by Ye and Yamamoto (2018) and also with the findings of the Ma and Wang (2019) study. Results clearly indicated reduced delays or impact on congestion when dedicated lane is provided on both Motorway and A-Road as compared to Motorway only. However, A-Road only case showed additional benefits overall, where A-Road innermost lane indicated least delays as compared to outermost side placement as well as other tested strategies and baseline scenario.

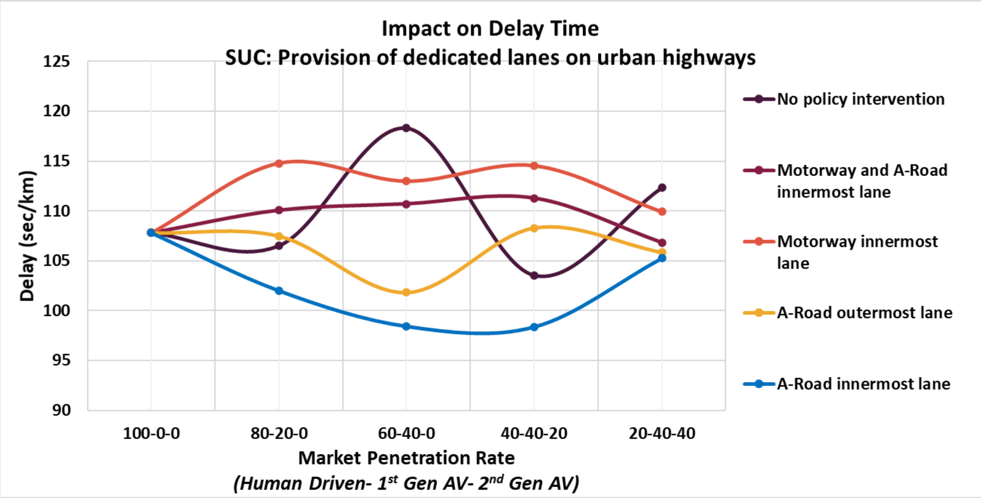


Figure 4.1 Impact on Delay Time due MPR of CAVs and provision of Dedicated Lane

Table 4.2 presents percentage change in delay time exclusively due to the provision of dedicated lane, calculated by taking the difference between delay time in a dedicated lane scenario and the corresponding baseline scenario. In terms or MPR scenario, maximum reduction in delays can be observed under moderate scenarios (60-40-0 and 40-40-20). With regard to the dedicated lane strategy, within the study network, overall A-road innermost lane scenario shows maximum reduction in delays as shown in Table 4.2.

Table 4.2: Percent Change in average delay time w.r.t corresponding Baseline for AV Dedicated Lane

Penetration Rate	Motorway and A Road innermost lane	Motorway innermost lane	A-Road outermost lane	A-Road innermost lane
80-20-0	3%	8%	1%	-4%
60-40-0	-6%	-4%	-14%	-11%
40-40-20	7%	11%	5%	-12%
20-40-40	-5%	-2%	-6%	-1%

4.1.2 Parking price policies

The trend of delays data can be seen in the following figure. This trend is similar to the trend observed for travel time (Figure 4.2). The delays do not follow any specific trend with respect to the market penetration rate. Further, the decreasing trend of delays can be observed for the baseline case.

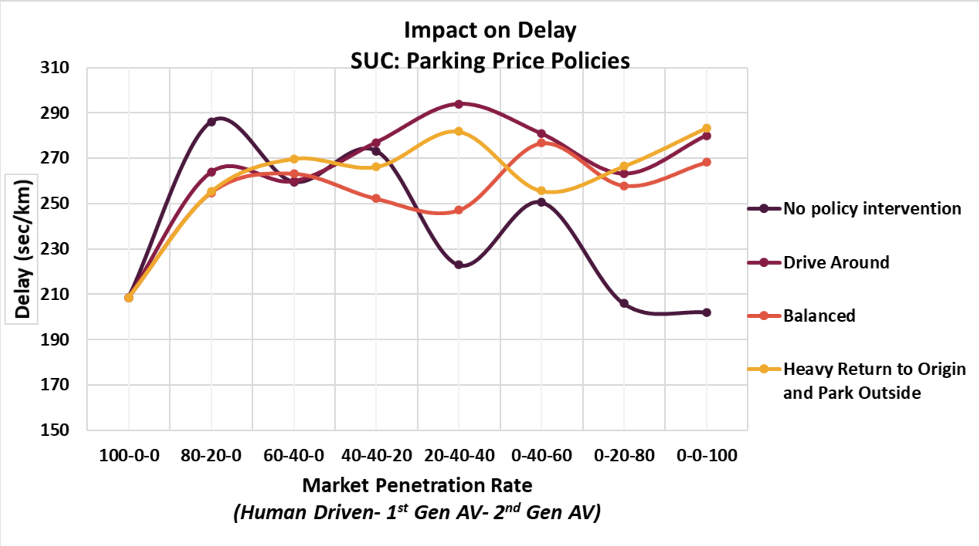


Figure 4.2 Impact on Delay Time due MPR of CAVs and provision of parking price policies

The percentage change in the delays based on the base case are shown in the following Table 4.3. The delays increase with the market penetration rate, which is contrary to the expectation with increment in market penetration rate. However, the reason for this could be the high volume of traffic on the roads, as most of the vehicles are not parked and they are roaming on the road to pick up the passenger again. It can be seen that the highest delays are present in the case of 'drive around' and 'heavy return to origin and park outside' scenarios. In both of these scenarios a major proportion of vehicles is on the road and waiting for the passengers to ride again. Whereas in the case of 'balanced' scenario some of the traffic is sent back to the parking spaces and the load on the roads is decreased hence, the delays are comparatively less on balanced scenario.

Table 4.3: Percent Change in average delay time w.r.t corresponding Baseline for parking price policies

Penetration Rate	Drive around	Balanced	Heavy Return to Origin and Park Outside
80-20-0	-7,8%	-10,9%	-10,8%
60-40-0	0,1%	1,4%	3,9%
40-40-20	1,3%	-7,7%	-2,6%
20-40-40	31,8%	10,8%	26,4%
0-40-60	12,1%	10,4%	2,0%
0-20-80	27,8%	25,3%	29,4%
0-0-100	38,6%	32,8%	40,3%

4.1.3 Parking space regulations

The impact on congestion of replacing on-street parking SUC is quantified by using the microsimulation results of average delay time KPI. In this SUC, on-street parking spaces have been replaced with various interventions i.e., removing half of the on-street parking, replaced with driving lane, cycle lane, pick-up/drop-off points and public spaces.

As seen in Figure 4.3 the higher value of average delay time corresponds to the scenario with lower CAVs market penetration rate, and lower values are associated with higher CAVs market penetration rate for baseline and all intervention scenarios. In other words, the average delay time decreases as the CAVs market penetration rate increases, and this trend can be clearly shown in Figure 4.3. This finding is in line with some previous studies that autonomous vehicles have the potential to reduce the delay time and improve the traffic efficiency in the traffic stream (Almobayedh, 2019; Li et al., 2019; Stogios et al., 2019; Stogios, 2018). It is worth noting that the least delay time occurs at the mixed scenarios i.e., 40-40-20 and 20-40-40 for baseline and other interventions. This is also consistent with the results of travel time presented in Section 4.1 in Deliverable 6.2 (Haouari et al., 2021). The results of average speed (shown in Figure 4.4) in this SUC demonstrated that higher average speeds were recorded in these two scenarios, resulting in reduced delay times and travel times in the traffic network.

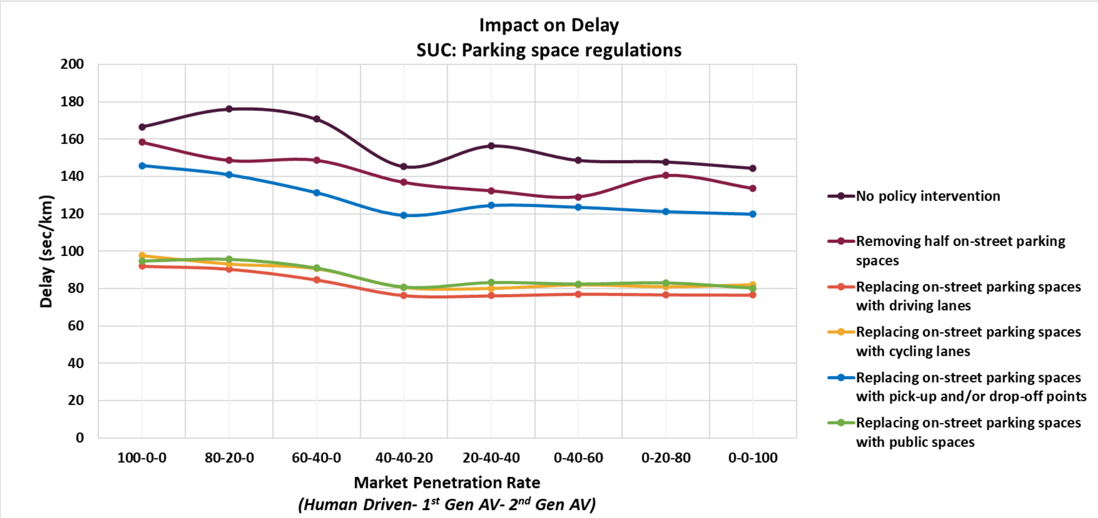


Figure 4.3: Impact on average delay time due to MPR of CAVs and interventions for parking space regulations SUC

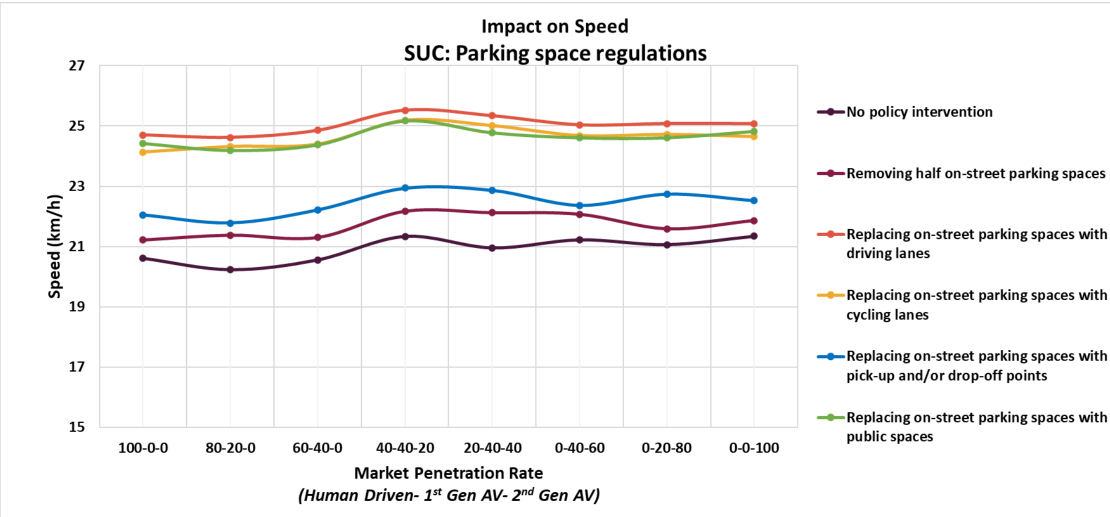


Figure 4.4 Impact on average speed due to MPR of CAVs and interventions for parking space regulations SUC

With respect to the impacts between the interventions, percentage change for average delay time at a certain MPR is calculated comparing to the value in the corresponding baseline MPR scenario, as shown in Table 4.4. It can be clearly seen that the interventions of replacing on-street parking with driving lane, cycle lane and public spaces have shown a significant improvement in reducing the delay time compared to the baseline scenario. Between 41% and 51% reduction can be achieved for these three interventions. In contrast, the interventions of removing half of the on-street parking spaces and replacing them with pick-up/drop-off points have less impact on delay time compared with the baseline scenario, and only 5% to 23% of the delay time was achieved. This is also consistent with the results of the travel time impacts in Deliverable 6.2, mainly because replacing the existing on-street parking with pick-up/drop-off points may generate a queue in a traffic stream while vehicles picking up and dropping off passengers, and eventually cause congestion to build up in the network. This finding is in line with other previous studies that indicated replacing on-street parking with pick-up/drop-off points could lead to excessive delays and increased travel times, which in turn would add more traffic congestion to the road network (Winter et al., 2021; Chai et al., 2020; ITF, 2018).

Table 4.4: Percent Change in average delay time w.r.t corresponding Baseline for parking space regulation replacing on-street parking SUC

CAVs Penetration Rate	Removing half on-street parking spaces	Replacing with driving lanes	Replacing with cycling lanes	Replacing with pick-up and/or drop-off points	Replacing with public spaces
100-0-0	-5,0%	-44,8%	-41,4%	-12,5%	-43,1%
80-20-0	-15,6%	-48,7%	-47,1%	-20,0%	-45,6%
60-40-0	-12,9%	-50,4%	-46,9%	-23,1%	-46,7%
40-40-20	-5,8%	-47,4%	-44,6%	-17,9%	-44,4%
20-40-40	-15,4%	-51,3%	-48,8%	-20,4%	-46,8%
0-40-60	-13,1%	-48,2%	-44,9%	-16,9%	-44,6%
0-20-80	-4,9%	-48,1%	-45,3%	-18,0%	-43,8%
0-0-100	-7,5%	-47,0%	-43,2%	-17,0%	-44,5%

4.1.4 Automated ride sharing

According to Figure 4.5, introducing an automated ridesharing service increases delay time for all market penetration rates compared to a no policy intervention baseline scenario. The results show that the increase in delay time is strongly related to the rate of travellers' (un) willingness to share their trips as well as CAVs market penetration rate, and this could be seen from the percentage change results calculated with respect to the baseline scenario for 20% served demand (Table 4.5). The results suggested that with a low willingness to share, there is an increasing impact on delay time compared with a high willingness to share rate. For example, under full MPR (0-0-100), the delay time decreases from 101,37 sec/km (+29%) with 20% willingness to share to 104,54 sec/km (+3%) when all served travellers are willing to share their rides. One of the most important potential reasons for the increasing impact on delay time is the increased number of trips and the empty VKT caused by making repositioning trips to reach new travellers. The circulating behaviour of shared vehicles (SAV) could also explain this increasing trend since they tend to use low capacity and/or secondary roads to reach their destinations, causing more traffic congestion (Overtoom, Correia, Huang, & Verbraeck, 2020). The results suggest that this negative impact could be reduced if more travellers are willing to use the proposed service as a shared-trip instead of an individual-trip service.

The results also reveal inconsistencies with the automation rate, which can be clearly seen from the varying trend presented in Figure 4.5. This inconsistency could be related to interactions between the mixed type of vehicles (i.e., conventional vehicles, 1st and 2nd generation CAVs) that cause additional congestion, especially under low MPR.

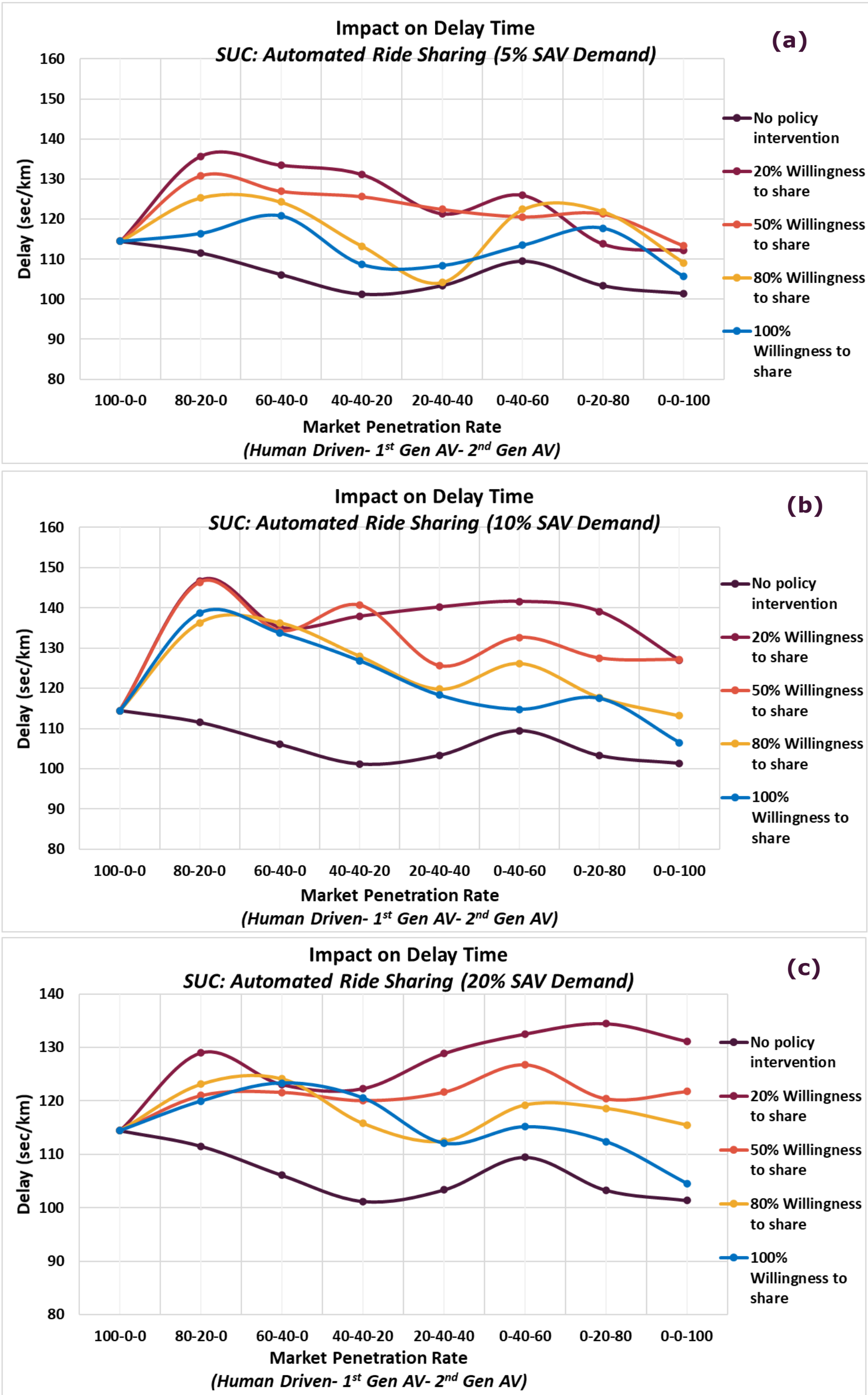


Figure 4.5: Impact on Delay Time due to MPR of CAVs and Automated ride sharing service

Table 4.5: Percent Change in average delay time w.r.t corresponding baseline for automated ridesharing scenarios under 20% served demand

Penetration Rate	20% Willingness to share	50% Willingness to share	80% Willingness to share	100% Willingness to share
80-20-0	16%	8%	10%	8%
60-40-0	16%	15%	17%	16%
40-40-20	21%	19%	14%	19%
20-40-40	25%	18%	9%	8%
0-40-60	21%	16%	9%	5%
0-20-80	30%	17%	15%	9%
0-0-100	29%	20%	14%	3%

4.1.5 Green Light Optimal Speed Advisory (GLOSA)

With the implementation of GLOSA system, considering advisory speeds sent by GLOSA are accurate and the drivers comply with them, the expectation is that such a technology will generate smoother traffic flow and reduce the number of stops and delays.

The simulation results from testing GLOSA system on one (case 1), two (case 2), and all three intersections (case 3) on the study network clearly showed decrease in delays with respect to no policy intervention (without GLOSA) scenario (Figure 4.6).

Maximum reduction in delays was observed when GLOSA was applied to all three intersections in the study corridor as compared to case 1 and case 2. It is important to note that the trend with respect to increasing MPR of CAVs, in all cases, is attributed to the baseline trend (no policy intervention curve).

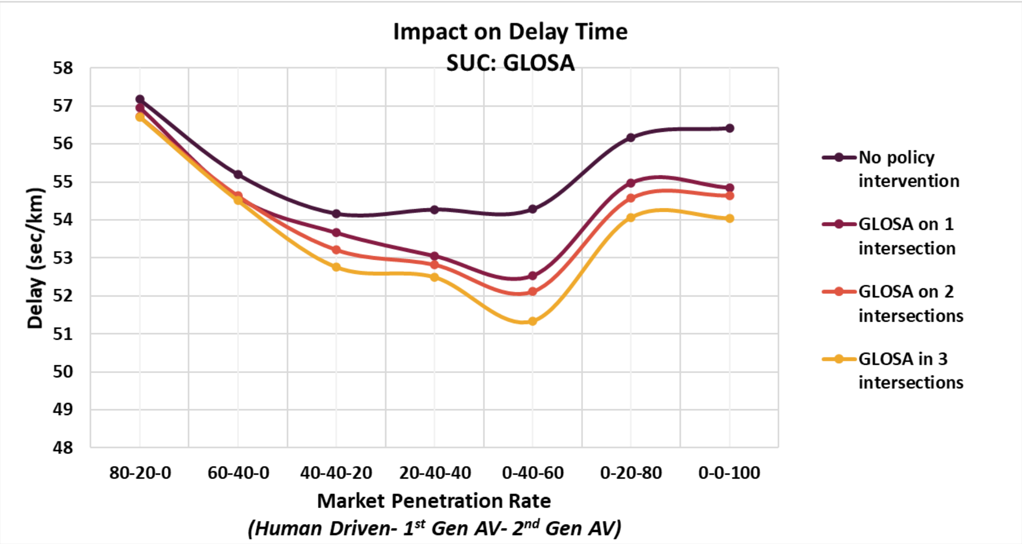


Figure 4.6: Impact on Delay due to MPR of CAVs and implementation of GLOSA system

Table 4.6 presents percentage change in delay (due to GLOSA) with respect to respective MPR baseline scenario. The results showed a maximum reduction of 5.4% at 0-40-60 MPR scenario while almost 4.2% reduction was observed at 100% MPR.

Table 4.6: Percent Change in average delay time w.r.t corresponding Baseline under GLOSA implementation scenarios

Penetration Rate	GLOSA on 1 intersection	GLOSA on 2 intersections	GLOSA in 3 intersections
80-20-0	-0,4%	-0,8%	-0,8%
60-40-0	-1,1%	-1,0%	-1,3%
40-40-20	-0,9%	-1,8%	-2,6%
20-40-40	-2,2%	-2,7%	-3,3%
0-40-60	-3,2%	-4,0%	-5,4%
0-20-80	-2,1%	-2,8%	-3,7%
0-0-100	-2,8%	-3,1%	-4,2%

4.2 Amount of travel

Within Levitate, the amount of travel is defined as the person kilometres of travel per year in an area. The estimate of the impact of automation on the amount of travel was made by using microsimulation, mesoscopic simulation (section 3.2), system dynamics and Delphi methods. Due to differences in the methods used to investigate this impact, some specific differences on the accessible data need to be mentioned:

- For the **microscopic simulation** approach: The indicator of total distance travelled by vehicles only [km] was chosen to measure the impact of amount of travel.
- For the **mesoscopic** activity chain **simulation**: The indicator of the average person's total distance travelled on a workday [km] was chosen to measure the impact of amount of travel.
- For the Delphi method: based on the experts' assumptions, interpretations, and predictions

4.2.1 Results from mesoscopic simulations – Road use pricing

In the context of the output extractable from the mesoscopic simulations, the impact of amount of travel was defined as the average over all agents on the simulated workday of the total distance that was traveled within the city boundaries (being the outline of the blue domain – the investigation perimeter in Figure 3.16). Considering that the RUP measure only affects part of that area (i.e., the inner-city region) any effect on the investigated impact will be damped.

The intent of implementing RUP for a chosen area is regional attenuation of the tolled modes of transport, which, in the presented scenarios are the conventional and automated passenger cars. Reduction in the use of tolled modes impacts the overall characteristics of the changed population of mobile agents and their trips between locations of activity.

Static RUP

Impact results of examining the effects on the average agent's travel distance for different static road use pricing schemes (as defined in section 3.2.3) are displayed in Figure 4.7. They show the simulated mobility behaviour when the entrance fee into the tolling area of the inner city (IC) is increased.

With the increase in automation levels, a minimal decrease (around -0.4 km ≈ -0.15 %) in average travel distances by person and workday can be seen (Figure 4.7) consistently for all RUP implementation levels. This effect, exhibiting diminishing distance reduction for highest automation availabilities, is most likely caused by the more frequently used automated vehicles which provide a very direct access to trip origins and destinations, thus shortening the walking stage that is necessary to access other less direct modes like public transport. Due to the missing model capabilities to describe the dropping of trips less necessary, no prominent changes are expected to be seen for this very aggregated impact. Very close lines for the no-RUP case and the first level (5 €) indicates that the lowest price implementation does not have a very strong effect with regards to the reduction in average travel distance. The maximum effect when comparing the no-RUP scenario versus the prohibitive pricing scenario shows a similar of reduction in travel distance as the change from no AVs to full automation.

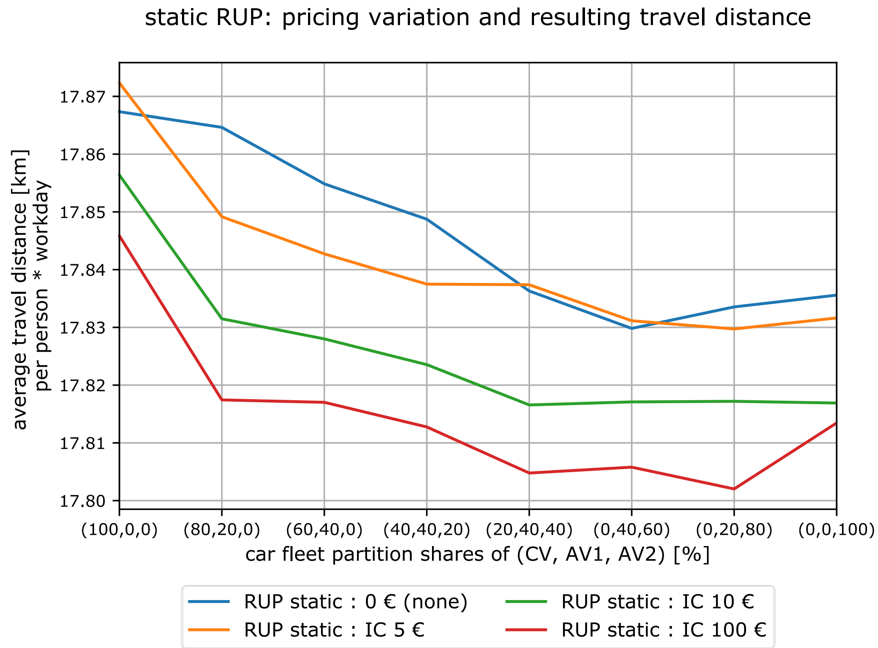


Figure 4.7: Static RUP - average agent daily travel distance within the city limits for the static RUP scenarios at increasing pricing levels, shown along an assumed evolution of increasing car fleet automation along the horizontal axis.

Dynamic RUP

Effects on the average agent's travel distance for different dynamic road use pricing schemes (as defined in section 3.2.3) are shown in Figure 4.8. The simulated mobility behaviour describes the situations when the fee per 7 km of distance driven inside the tolling area of the inner city (IC) is increased in steps equivalent to the prices defined before. In these scenarios not all vehicles entering the tolling area will be charged equally high fees, as some of the agents only cross into the IC briefly to soon leave again, therefore only amounting to low tolling costs.

The no tolling scenario (Figure 4.8) shows the most explicit, though small reduction in resulting average travel time for increasing automation levels, which amounts to -0.4 km (≈ -0.15 %). Comparing the case of dynamic RUP to the previous case of static RUP, brings the attention to a surprising "inversion case" where moderate RUP pricing levels show a higher resulting average travel distance than the case of no-RUP implementation or the prohibitive case of a maximum tolling level (100 €). This is an example of the agents willing to exchange lower monetary trip costs for increased travel time, and a comparison to the results on the impact of average travel time presented in deliverable D6.2 shows almost no reductions in travel time for the case of dynamic RUP implementation. The moderate pricing levels cause the agents to circumvent the tolling area and only let the very last sections of their trips take them inside this area, which is a strategy that will not save costs for the static RUP scenario. Maximum differences over all scenarios in average travel distance amount to 0.3 %.

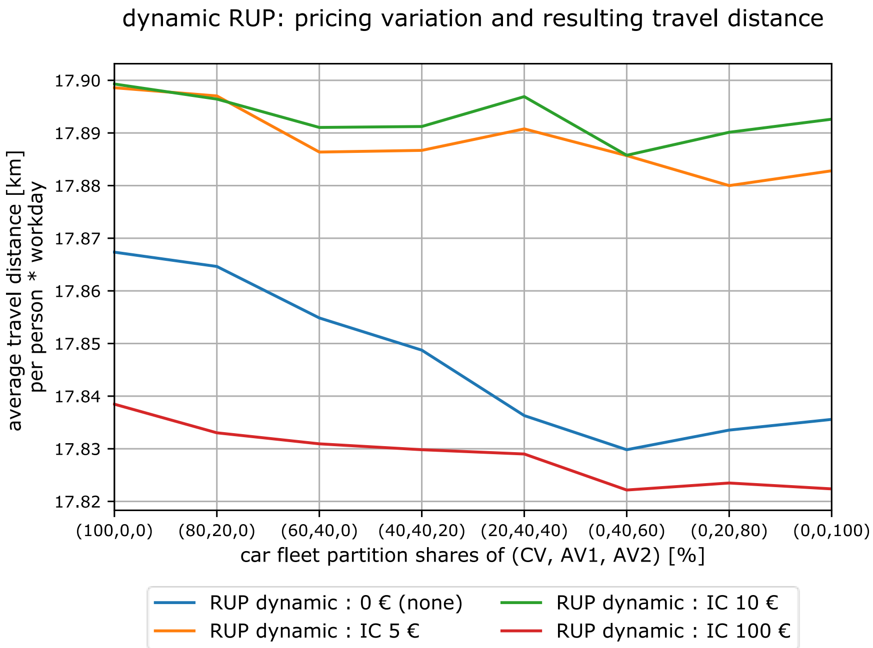


Figure 4.8: Dynamic RUP - average agent daily travel distance within the city limits for the dynamic RUP scenarios at increasing pricing levels, shown along an assumed evolution of increasing car fleet automation along the horizontal axis.

Marginal utility of money (mUoM)

To investigate effects on the average travel distance under the assumption of changed monetary value, simulations were made to assume monetary value shifts of +/- 5%, which cause the simulated agents to reconsider their mobility behaviour with respect to the monetary cost shares (as opposed to time-costs).

Again, in Figure 4.9 the average travel distances by person do decrease with increasing levels of automation, where shorter access paths to more frequently used automated passenger cars do explain this effect. The decrease for this very aggregated impact quantity is in the range of -0.4 km (≈ -0.15 %) and it shows consistent across all mUoM levels that were investigated. At a reduced mUoM (= 0.95), which allows the agents to spend money more freely, longer travel distances are acceptable, while the increased mUoM shows the expected opposite effects.

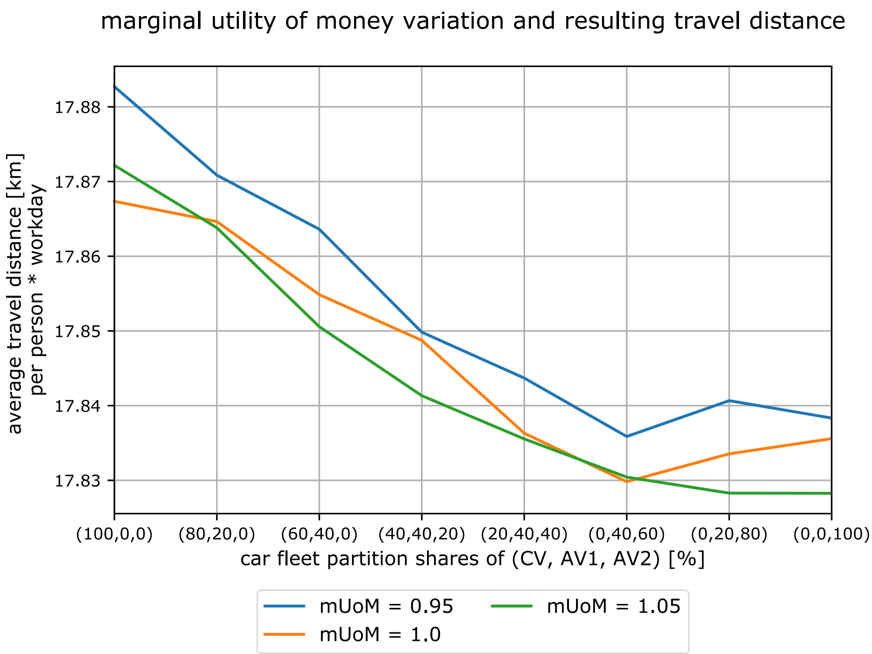


Figure 4.9: No RUP scenarios (0 € toll) - average agent daily travel distance within city limits for the no RUP scenarios and varied levels of the marginal utility of money, shown for an assumed evolution of increasing car fleet automation along the x-axis

4.2.2 Results from microscopic simulations

4.2.2.1 Provision of dedicated lanes *on urban highways*

The impact of dedicated lanes on total distance travelled was analysed through microsimulation output. The results are presented through the following plot (Figure 4.10) showing the total distance travelled in km against MPR of CAVs under baseline and other analysis scenarios. As observed in Figure 4.10, on average, maximum distance travelled is higher in case of 'A road innermost lane'. This can be explained by the shorter travel time (Haouari et al., 2021) and delays (see Figure 4.1) under this case, which indicates improved traffic flow due to which there is overall more distance travelled in the system. Whereas under other scenarios, the higher delays indicate interrupted flow (Figure 4.1) leading to lower distance travelled compared to 'A road innermost lane'. However, maximum distance travelled can be observed under moderate scenario after which the flow is affected with increasing MPR as only one dedicated lane is considered in this analysis. In this regard, (Ma and Wang (2019) have shown that for CAVs percentage between 10 to

40% one dedicated lane whereas at the higher percentages ranging from 50 to 90% two dedicated lanes can provide optimal capacity.

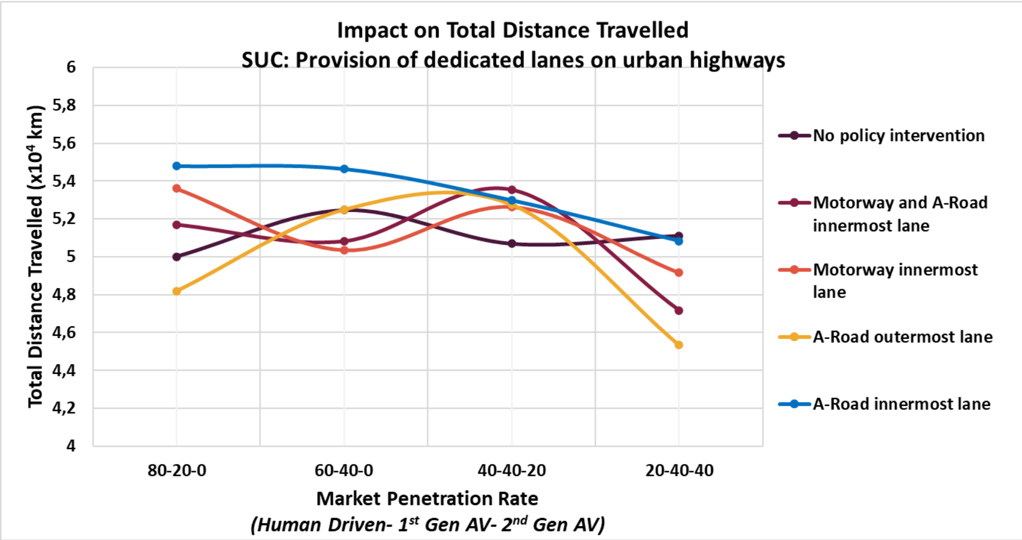


Figure 4.10: Impact on Total Distance Travelled due to MPR of CAVs and Dedicated Lanes

Table 4.7 presents percentage change in total distance travelled due to different dedicated lane configurations on A road and motorway on the study network. The percentage change is calculated by taking the difference from the respective baseline MPR scenario. Overall, results show increased distance travelled under A-road innermost lane scenario as compared to the other scenarios.

Table 4.7: Percent Change in total distance travelled w.r.t corresponding Baseline for AV Dedicated Lane

Penetration Rate	Motorway and A Road innermost lane	Motorway innermost lane	A-Road outermost lane	A-Road innermost lane
80-20-0	3%	7%	-4%	10%
60-40-0	-3%	-4%	0%	8%
40-40-20	6%	4%	4%	-1%
20-40-40	-8%	-4%	-11%	8%

4.2.2.2 Parking price policies

The total distance travelled by the vehicles in all the scenarios considered is shown in Figure 4.11. It can be seen that the distance travelled by the vehicles in most of the cases is almost the same. However, the distance travelled in the case of 'drive around' decreases with the increment of market penetration rate. This could be caused by the congestion on the roads, as vehicles were not allowed to return to the parking spaces and the volume of traffic increased with the market penetration rate of AVs.

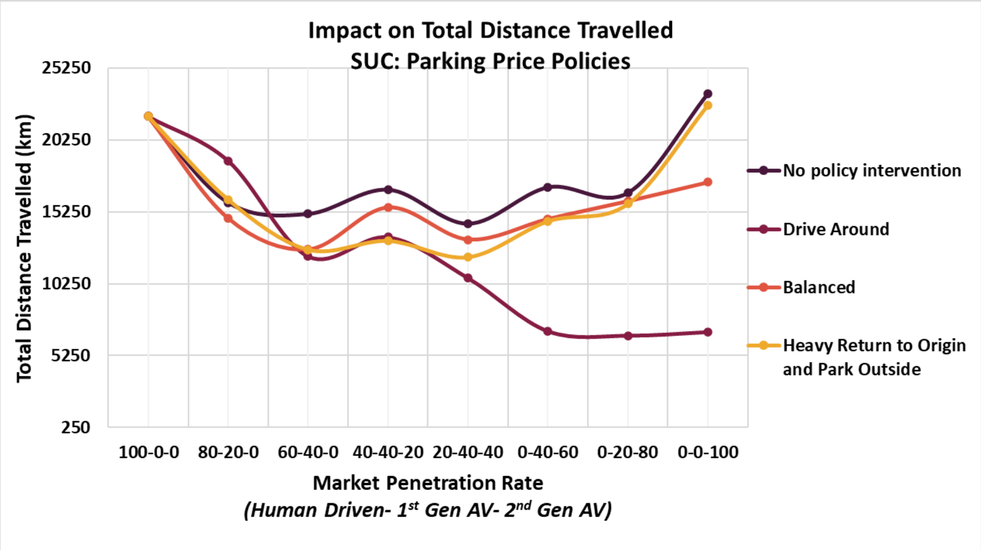


Figure 4.11: Impact on Total Distance Travelled due to MPR of CAVs and Parking price policies

The change in the travel distance with regards to baseline can be seen in Table 4.8. It can be seen that most of the change occurs in the case of the 'drive around'. As discussed earlier, the reason for this could be the presence of a heavy volume of traffic on the road. In the remaining cases, this change remains almost the same.

Table 4.8: Percent Change in total distance travelled w.r.t corresponding Baseline for various parking policies

Penetration Rate	Drive around	Balanced	Heavy Return to Origin and Park Outside
80-20-0	18,4%	-6,9%	1,3%
60-40-0	-19,5%	-16,4%	-16,4%
40-40-20	-19,6%	-7,3%	-21,2%
20-40-40	-26,2%	-7,6%	-16,1%
0-40-60	-59,0%	-13,0%	-13,9%
0-20-80	-59,9%	-3,5%	-4,6%
0-0-100	-70,6%	-26,3%	-3,4%

4.2.2.3 Parking space regulations

The results with an absolute value of total distance travelled by the vehicles for baseline and all interventions based on CAVs fleet market penetration level is presented in Figure 4.12. It can be seen that the distance travelled for interventions of replacing on-street parking with driving lane, cycle lane and public spaces are almost levelled as the CAVs market penetration rate increases. Whilst the interventions of removing half of the on-street parking spaces and replacing them with pick-up/drop-off points have shown a significant fluctuation with CAVs penetration levels. One of the most important potential reasons is that the interventions of removing half of the on-street parking spaces and replacing them with pick-up/drop-off points may often create stops and queues in the traffic stream due to frequent parking manoeuvres or vehicles picking up and dropping off passengers and leading more congestions and delays.

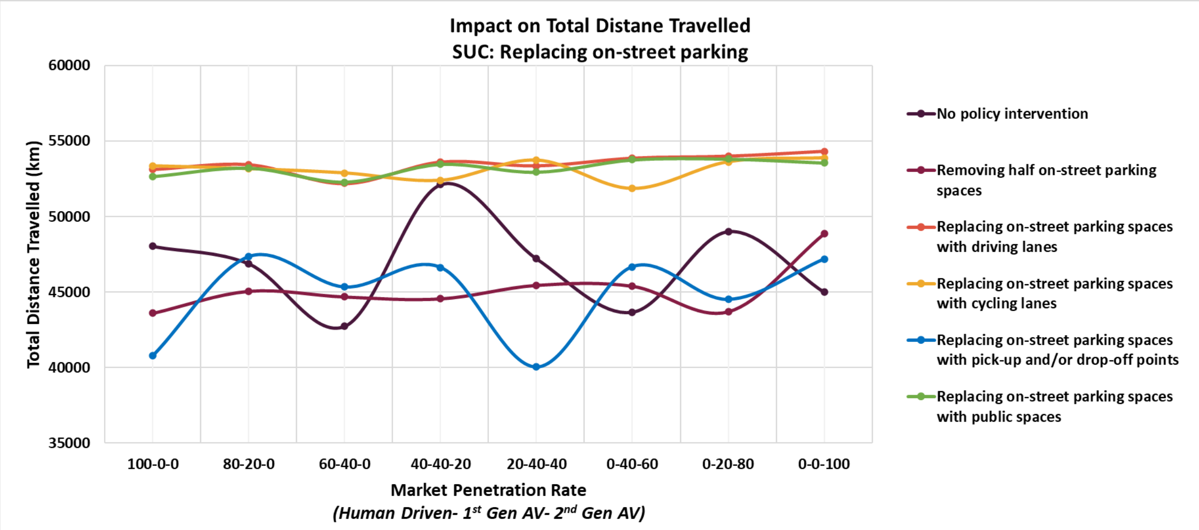


Figure 4.12: Impact on total distance travelled due to MPR of CAVs and interventions parking space regulations SUC

The impacts between the interventions are shown in Table 4.9. where the total distance travelled for vehicles is calculated as a percentage change comparing to the value in the corresponding baseline MPR scenario. It can be clearly seen the interventions of replacing on-street parking with driving lane, cycle lane and public spaces show a general increased distance travelled compared to the baseline scenario. In contrast, the interventions of removing half of the on-street parking spaces and replacing them with pick-up/drop-off points have decreased distance travelled compared to the baseline scenario, for example, the total distance travelled has reduced by around 15% and 11% at 40-40-20 scenarios for the interventions of removing half of the on-street parking spaces and replacing with pick-up/drop-off points, respectively. This can be expected because of the reason that was discussed previously. Also, the interventions of replacing on-street parking with driving lane, cycle lane and public spaces have a better traffic performance in the network compared to those with removing half of the on-street parking spaces and replacing them with pick-up/drop-off points, i.e., less delay, less travel time (discussed in Deliverable 6.2) and increased traffic flow. In other words, more vehicles enter the network which in turn increase the total distance travelled.

Table 4.9: Percent Change in total distance travelled w.r.t corresponding Baseline for parking space regulations SUC

CAVs Penetration Rate	Removing half on-street parking spaces	Replacing with driving lanes	Replacing with cycling lanes	Replacing with pick-up and/or drop-off points	Replacing with public spaces
100-0-0	-9,2%	10,6%	11,1%	-15,0%	9,6%
80-20-0	-3,9%	14,0%	13,4%	1,0%	13,5%
60-40-0	4,5%	22,1%	23,7%	6,1%	22,3%
40-40-20	-14,5%	2,9%	0,5%	-10,5%	2,6%
20-40-40	-3,7%	13,0%	13,8%	-15,2%	12,1%
0-40-60	3,9%	23,4%	18,7%	6,9%	23,1%
0-20-80	-10,8%	10,2%	9,4%	-9,2%	9,8%
0-0-100	8,6%	20,7%	19,8%	4,9%	19,0%

4.2.2.4 Automated ride sharing

The impact of introducing an automated ride-sharing service on the amount of travel was quantified through the total distance travelled output coming from microsimulation. The results shown in Figure 4.13 suggest that the impact of the introduced service on total distance travelled depends on CAVs market penetration rates (MPR), the served demand, and finally, the travellers' willingness to share (their preference of using this service as an individual or shared trip service). The effect of CAVs (MPR) could be clearly seen from the irregular trend of the no policy baseline scenario, where the results show inconsistency with the increased automation rate. This could be related to interactions between the mixed type of vehicles (i.e., conventional vehicles, 1st, and 2nd generation CAVs) that cause additional congestion, especially under low MPR. This trend is also observed in all the interventions studied under this SUC. In terms of served demand, the results show a significant difference in curves' trends going from 5% to 20% served demand. For 5% served demand (Figure 4.13 (a)), we can see mixed trends regarding baseline. In general, an increase in VKT is expected with the introduction of automated shared services due to empty repositioning trips (pick-up trips) (Narayanan et al, 2020). However, results from Figure 4.13(a) show a reduction in some scenarios compared to the baseline due to having less traffic flow due to congestion (see delay results Figure 4.5). With higher SAV demands (10% and 20%), the results show an increase in total travelled distance with higher willingness to share values (80% and 100%) compared to no policy baseline scenario, while a reduction was observed with low and medium willingness to share values (20% and 50%). With low willingness to share, many travellers will use the SAVs as a taxi or car-sharing system, which means less vehicle occupancy and more VMT due to empty trips (Vosooghi et al., 2019), which is not the case with the obtained results. This inconsistency is due to traffic congestion that prevents SAVs from finishing their scheduled trips and many vehicles from entering the network by the end of the simulation period which could clearly be seen from the traffic flow (Figure 4.14) and delay results (Figure 4.5).

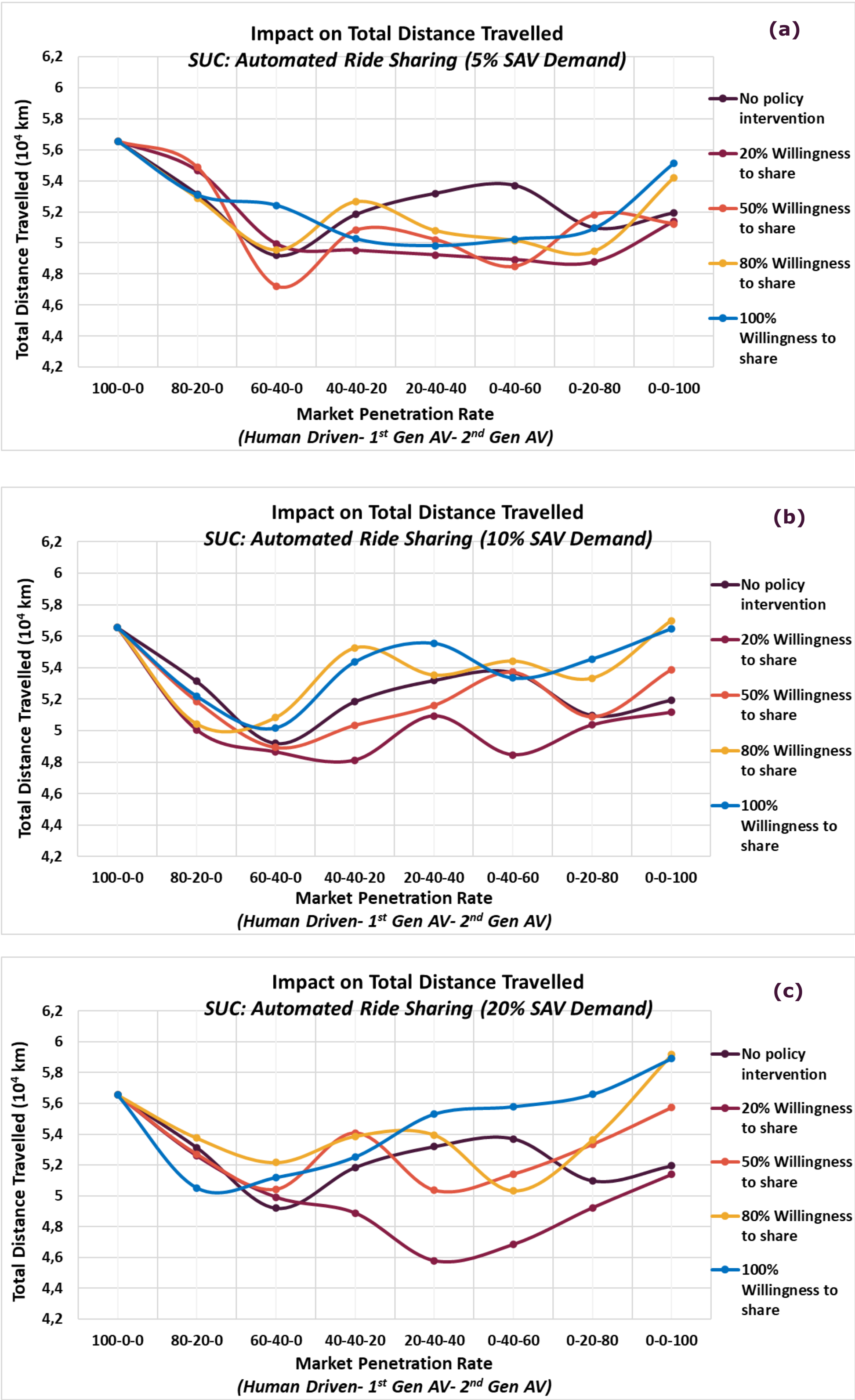


Figure 4.13: Impact on total distance travelled due to MPR of CAVs and Automated ride sharing

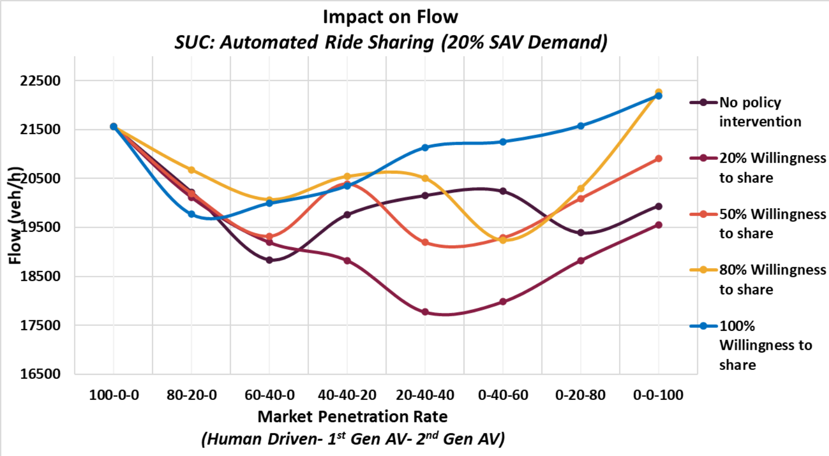


Figure 4.14: Impact on total distance travelled due to MPR and automated ridesharing service for 20% SAV demand

4.2.2.5 Green Light Optimal Speed Advisory (GLOSA)

The microsimulation results on total distance traveled showed irregular trend with increasing MPR of AVs. However, on average, implementation of GLOSA shows increase in distance travelled when compared with the baseline curve. Additionally, the results also suggest increase in distance travelled with implementation on multiple intersections in the study network (Figure 4.15). In terms of microsimulation output, this shows improved flow and more vehicles being able to complete their journey during the simulation period.

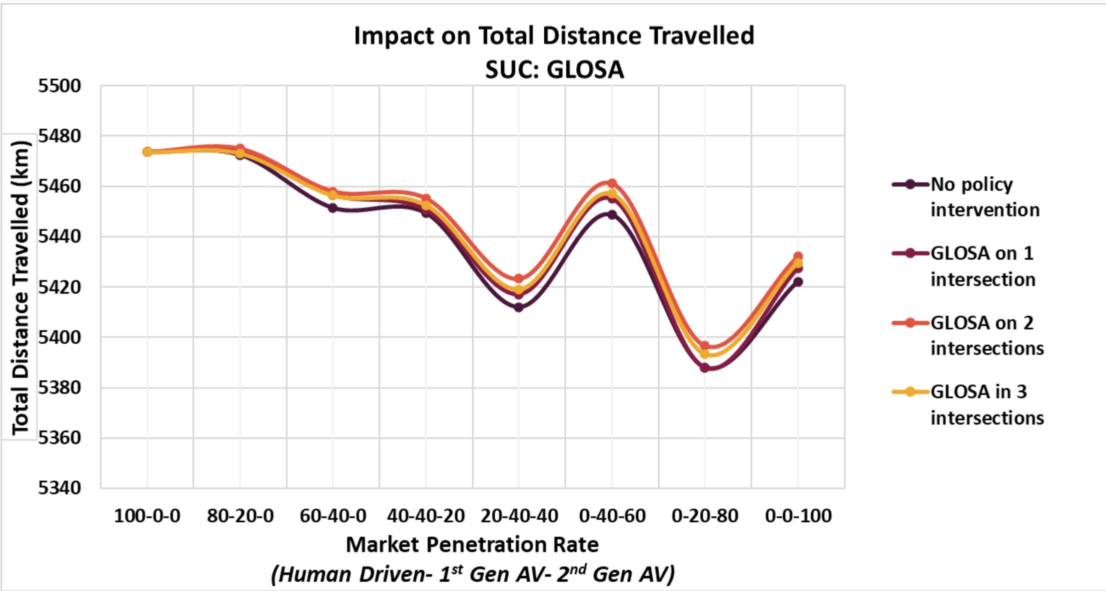


Figure 4.15: Impact on Total Distance Travelled due to MPR of CAVs and GLOSA

Table 4.10 presents percentage change in total distance travelled due to implementation of GLOSA system, calculated by taking the difference of impact between with and without GLOSA scenarios at each MPR of AVs. Overall, there is not a significant change in distance travelled with implementation of GLOSA system under all implementation scenarios, as shown in Table 4.10.

Table 4.10: Percent Change in total distance travelled w.r.t corresponding Baseline for GLOSA

Penetration Rate	GLOSA on 1 intersection	GLOSA on 2 intersections	GLOSA in 3 intersections
80-20-0	0,03%	0,05%	0,01%
60-40-0	0,10%	0,12%	0,09%
40-40-20	0,02%	0,11%	0,06%
20-40-40	0,09%	0,21%	0,13%
0-40-60	0,12%	0,23%	0,16%
0-20-80	0,00%	0,16%	0,10%
0-0-100	0,10%	0,18%	0,14%

4.2.3 Results from Delphi

4.2.3.1 Road use price

The general experts' opinion was that the introduction of automation in the urban environment will progressively increase the amount of travel, reaching 25,4% in the long term (Figure 4.16). Regarding the city toll scenarios, they all reduce the amount of travel, but all the negative impact is minimized in the long term. The scenario of empty km pricing will reduce from 9,6% to 5,7% with the increase of AVs market penetration rate. Similarly, static city toll will lead to an increase from -15,6% to -3,6%, presenting the largest variation depending on the AVs market penetration rate. Finally, dynamic city toll will increase the amount of travel from -12,1% in the short term to -5,6% in the long term.

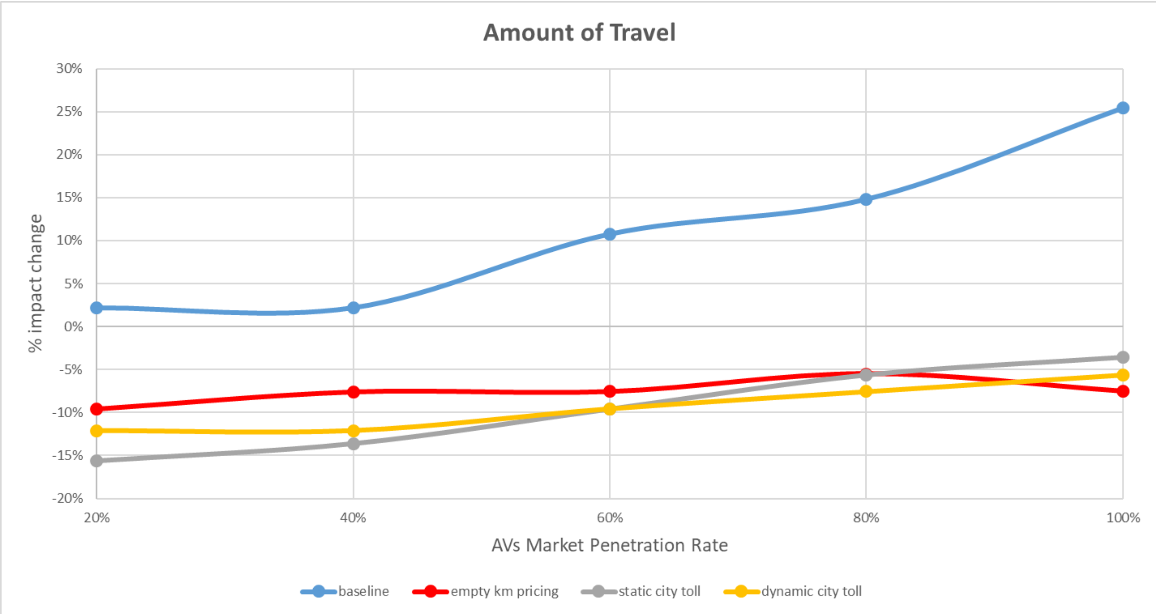


Figure 4.16: 1st round Delphi amount of travel results for the city toll scenarios

The majority of the 2nd round participants stated that they definitely (14%-43%) or moderately (43%-86%) agree with the resulted 1st round trends (Figure 4.17). Some experts slightly (14%) agreed with the baseline scenario and the empty km pricing scenario curves and suggested that all studied scenarios will positively (5%-10%) affect the amount of travel.

Figure 4.17: 2nd round Delphi amount of travel results for baseline and static city toll

4.2.3.2 Provision of dedicated lanes on urban highways

The general experts' opinion was that the introduction of AVs in the urban environment will increase (30,8%) the amount of travel (Figure 4.18). Regarding AVs dedicated lanes scenarios, they all presented some oscillations depending on AVs market penetration rate, but all increased amount of travel in the long term. The scenario of an AV dedicated lane on the outermost motorway lane, as well as the dynamically controlled AV dedicated lane will mostly affect the studied impact, among the other AV dedicated lane scenarios, reaching an increase of 14,7% and 14,2% respectively. The AV dedicated lane on the innermost motorway lane will not significantly affect the amount of travel, reaching a maximum of 4,2% for 60% AVs market penetration rate.

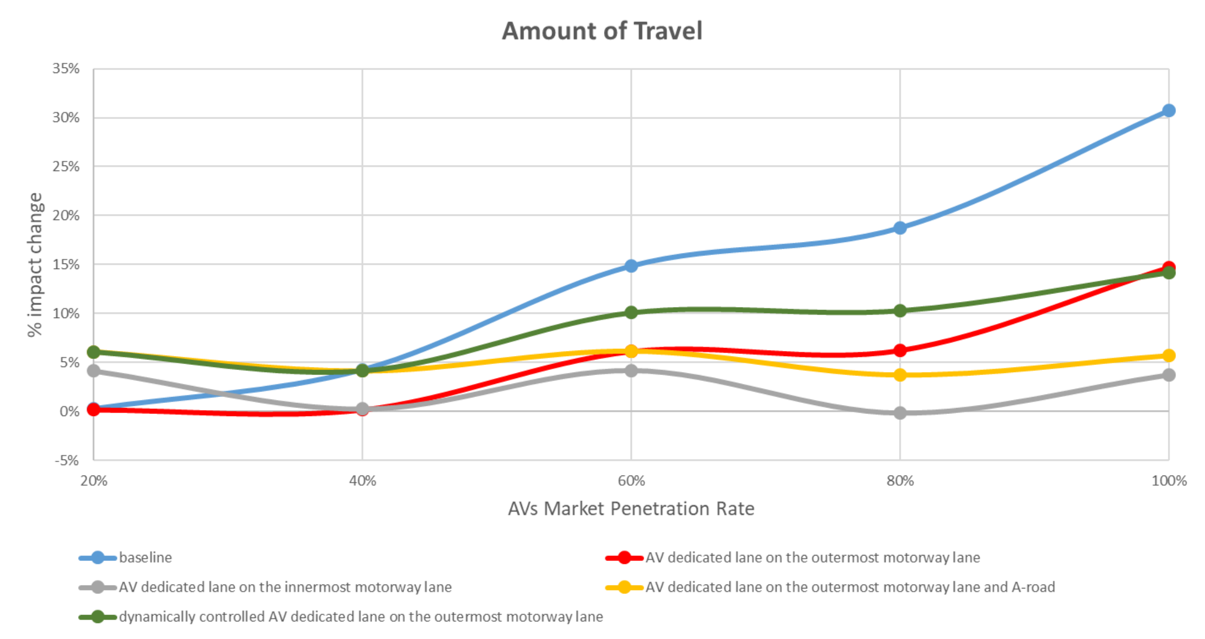


Figure 4.18: 1st round Delphi amount of travel results for the AV dedicated lanes scenarios

In the second Delphi round all experts moderately agreed with the resulted trend for the baseline scenario (Figure 4.19). Additionally, the majority of 2nd round participants stated that they definitely (34%) or moderately (33%) agree with the curves of the AV dedicated lanes scenarios. Some experts suggested that none of the scenarios will significantly affect the amount of travel.

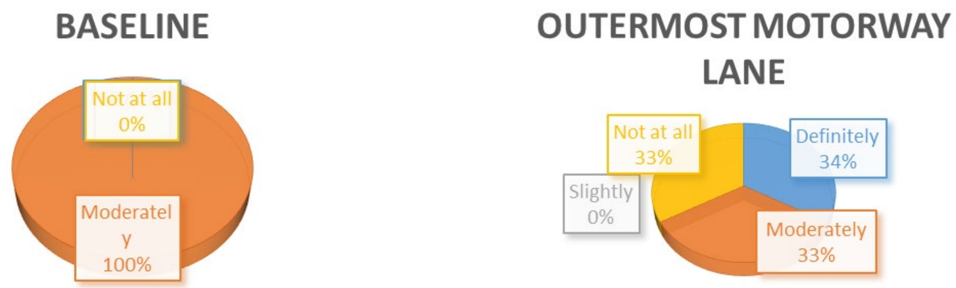


Figure 4.19: 2nd round Delphi amount of travel results for baseline and AV dedicated lane on the outermost motorway lane scenarios

4.2.3.3 Parking price policies

The general experts' opinion was that the introduction of AVs in the urban environment will increase the amount of travel (Figure 4.20). More precisely, the introduction of AVs will lead to an increase of up to 46,5% of the amount to travel for 100% AVs market penetration rate. Regarding, the CAVs parking behaviours, parking outside, driving around and returning to origin will increase the amount of travel by 28,4%, 25,9% and 11,5% respectively, since they all require more driving and thus more empty kilometres.

According to 1st round results CAVs parking inside will not affect the studied impact regardless of the AVs market penetration rate.

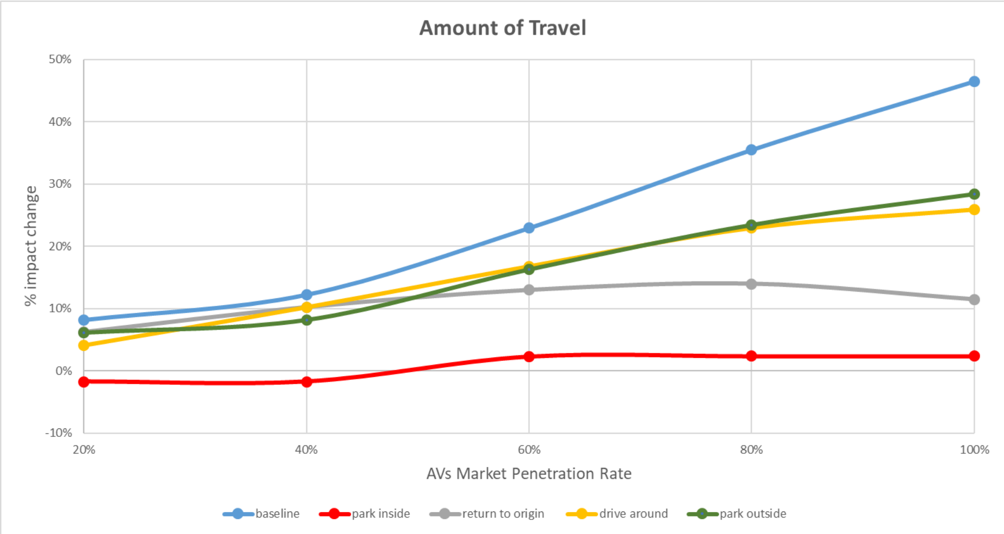


Figure 4.20: 1st round Delphi amount of travel results for CAV parking price policies scenarios

In the second Delphi round the majority of the experts stated that they agree definitely (50%) or moderately (16%-33%) with the curves of the 1st round (Figure 4.21). Regarding the CAVs parking inside scenario two experts suggested that this sub-use case will also increase the amount of travel by 15%, like the other parking behaviour scenarios.

Figure 4.21: 2nd round Delphi amount of travel results for baseline and CAVs parking inside scenarios

4.2.3.4 Parking space regulations

The general experts' opinion was that the introduction of AVs in the urban environment will increase the amount of travel. More precisely, the introduction of AVs will lead to an increase of up to 32,5% of the amount to travel for 100% AVs market penetration rate (Figure 4.22). Regarding, the parking regulations sub-use cases, replacing on-street parking with driving lanes will increase the most the amount of travel among the other parking regulation scenarios reaching 17,9% for AVs market penetration rate of 100%. Replacing on-street parking space with them for public use or with pick-up/drop-off parking space will not affect amount of travel in the long term.

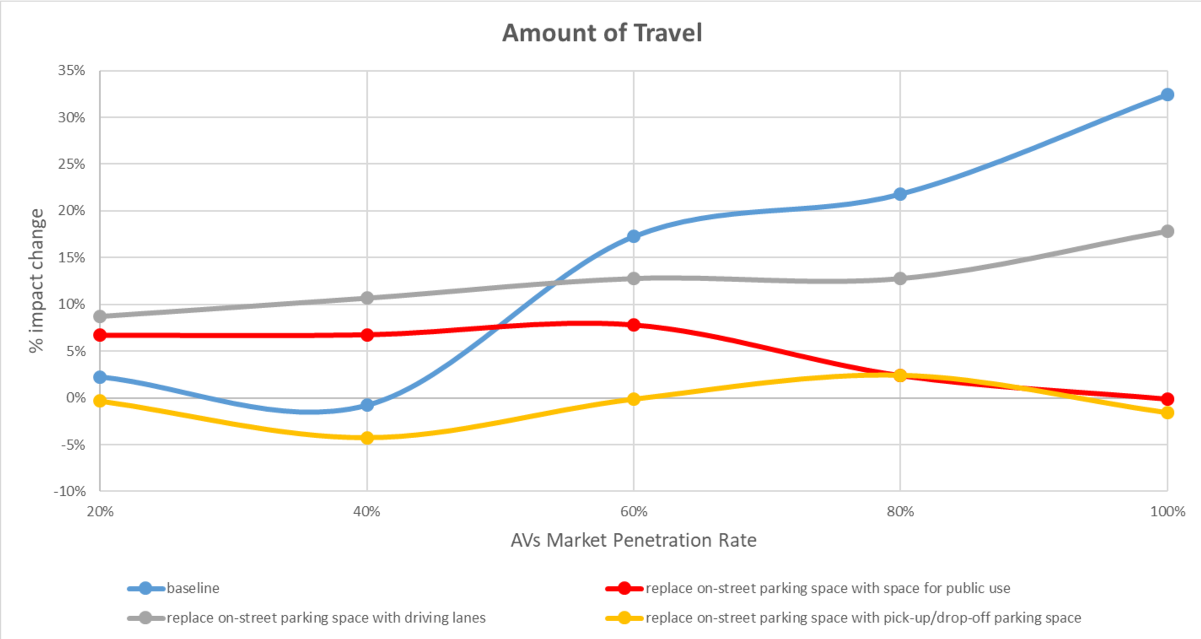


Figure 4.22: 1st round Delphi amount of travel results for parking space regulation scenarios

In the second Delphi round all the experts stated that they agree definitely (60%-100%) or moderately (0%-40%) with the curves of the 1st round (Figure 4.23).

Figure 4.23: 2nd round Delphi amount of travel results for baseline and replacing on-street parking with spaces for public use

4.2.3.5 Automated ride sharing

The general experts' opinion was that the introduction of AVs and automated ridesharing in the urban environment will progressively increase the amount of travel, reaching 36,4% and 42% respectively in the long term (Figure 4.24).

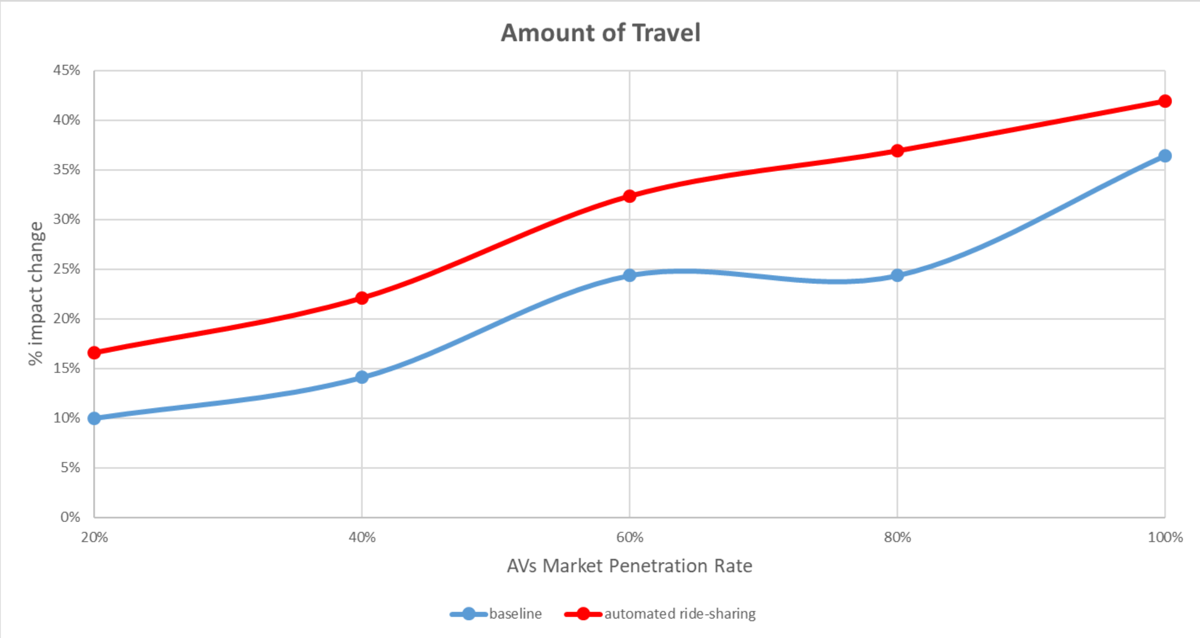


Figure 4.24: 1st round Delphi amount of travel results for the automated ridesharing scenarios

The majority of 2nd round participants stated that they definitely (16%) or moderately (50%-67%) agree with the resulted 1st round trends for the automated ride sharing and the baseline scenarios (Figure 4.25). Some experts (17%-33%) stated that the 1st round impact of ridesharing and of the baseline scenario on the amount of travel is overestimated and proposed an average improvement of 15% and 10% respectively.

Figure 4.25: 2nd round Delphi amount of travel results for baseline and automated ridesharing

4.2.3.6 Green Light Optimal Speed Advisory (GLOSA)

The general experts' opinion was that the introduction of AVs in the urban environment will progressively increase the amount of travel, reaching 36,4% in the long term (Figure 4.26). Regarding the GLOSA scenario, experts' answers indicated that there will be an improvement of 10% to 16% on amount of travel, depending on AVs market penetration rate.

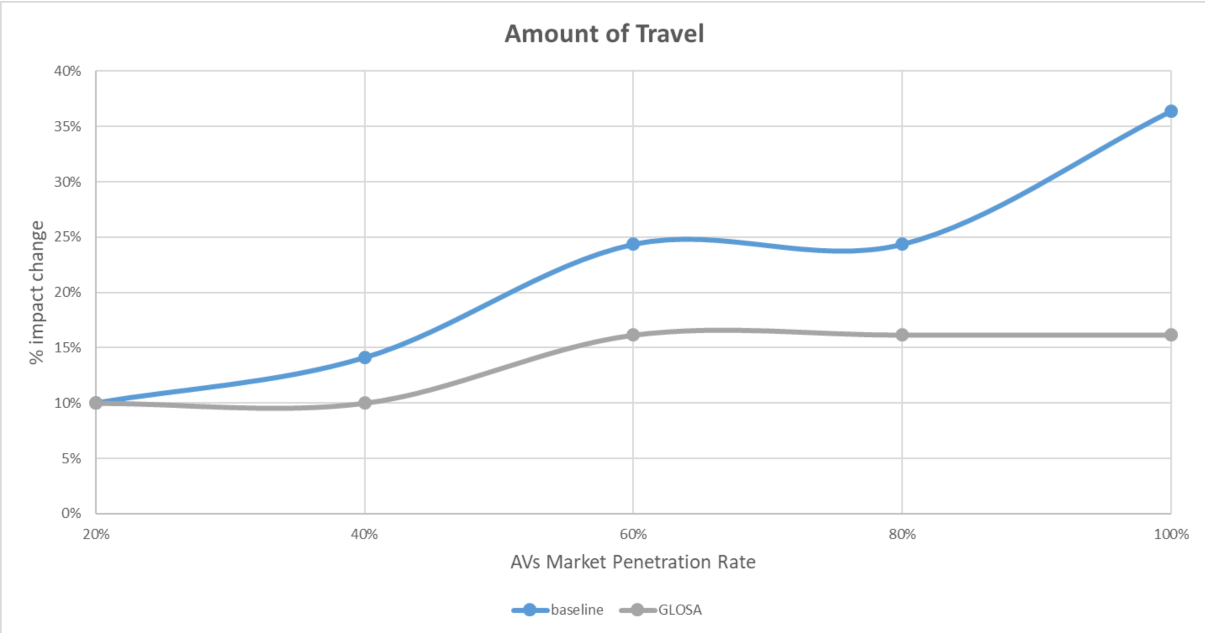


Figure 4.26: 1st round Delphi amount of travel results for GLOSA scenarios

The majority of 2nd round participants stated that they definitely (16%) or moderately (50%-67%) agree with the resulted 1st round trends for the baseline scenarios. Some experts (17%-33%) stated that the 1st round impact of the baseline scenario on the amount of travel is overestimated and proposed an average improvement of 10%. According to 50% of experts GLOSA will not at all affect the studied impact (Figure 4.27).

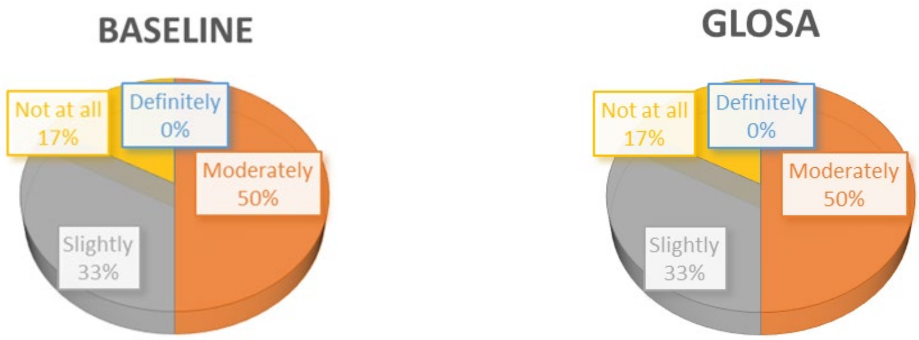


Figure 4.27: 2nd round Delphi amount of travel results for baseline and GLOSA

4.3 Modal split using public transport

The impact of the introduction of the various automation scenarios on modal split using public transport (% of trip distance made using public transportation) is estimated by the mesoscopic simulation, system dynamics and the Delphi methods.

4.3.1 Results from mesoscopic simulation - Road use pricing

For the mesoscopic simulation the modal split was determined as the share by distance of trips carried out using that main transport mode (as defined above) as a fraction of the total distance travelled in any available mode within the city boundaries (being the outline of the blue domain – the investigation perimeter in Figure 3.16). The RUP measure only affects part of that area (i.e., the inner-city region), which must be taken into account.

The transport mode of a trip is classified according to its *longest distance mode* (ldm), meaning the largest part of the overall distance has been covered by using a bus, for example. No matter what the ldm of one specific trip may be, they mostly are composed of stages of different modes, including at least access and egress walking to and from other modes of transport.

Based on the mode classification of each trip it is apparent, that the modal split for public transport as defined here will preferably concern longer trips, as opposed to the modal split for active transport described in section 4.4.1.

The intent of implementing RUP for a chosen area is regional attenuation of the tolled modes of transport, which, in the presented scenarios are the conventional and automated passenger cars. Reduction in the use of tolled modes impacts the overall characteristics of the changed population of mobile agents and their trips between locations of activity.

Static RUP

Impact results of examining the effects on the public transport mode share by distance for different static road use pricing schemes (as defined in section 3.2.3) are displayed in Figure 4.28. They show the simulated mobility behaviour when the entrance fee into the tolling area of the inner city (IC) is increased.

Increasing automation levels lead to a decline of the public mode split by about 4 %, for all investigated static RUP implementation schemes, as can be seen in Figure 4.28. The limit case of prohibitive tolling prices (100 €) raises the public mode split by a total of 15 %, when compared to the no-RUP scenario. It is noteworthy however, that this increase of an impact defined for the whole city area is caused by the regionally limited implementation of RUP within the inner city alone.

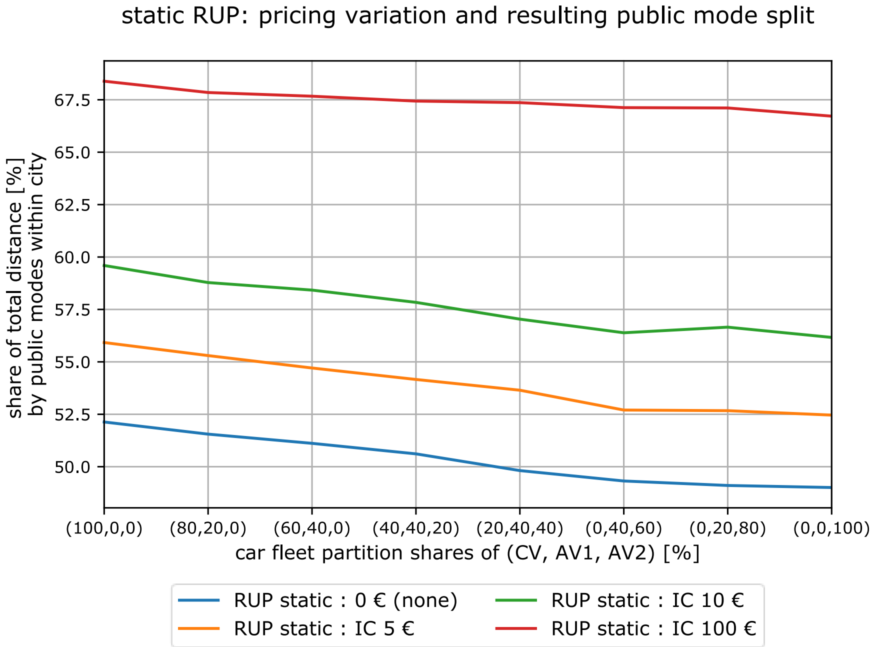


Figure 4.28: Static RUP - public modes' distance share within the city limits for the static RUP scenarios at increasing pricing levels, shown along an assumed evolution of increasing car fleet automation along the horizontal axis.

Dynamic RUP

Effects on the public transport mode share by distance for different dynamic road use pricing schemes (as defined in section 3.2.3) are shown in Figure 4.29. The simulated mobility behaviour describes the situations when the fee per 7 km of distance driven inside the tolling area of the inner city (IC) is increased in steps equivalent to the prices defined before. In these scenarios not all vehicles entering the tolling area will be charged equally high fees, as some of the agents only cross into the IC briefly to soon leave again, therefore only amounting to low tolling costs.

A decline in the public mode split by roughly 5 % is visible in Figure 4.29, for all investigated static RUP implementation schemes and increasing automation levels. The limit case of prohibitive tolling prices (100 €) raises the public mode split by a total of 15 %, when compared to the no-RUP scenario. The effect of increasing prices is a little smaller than for the static RUP implementation, because short trips into the tolling area are only affected in a small way. It is noteworthy however, that this increase of an impact defined for the whole city area is caused by the regionally limited implementation of RUP within the inner city alone.

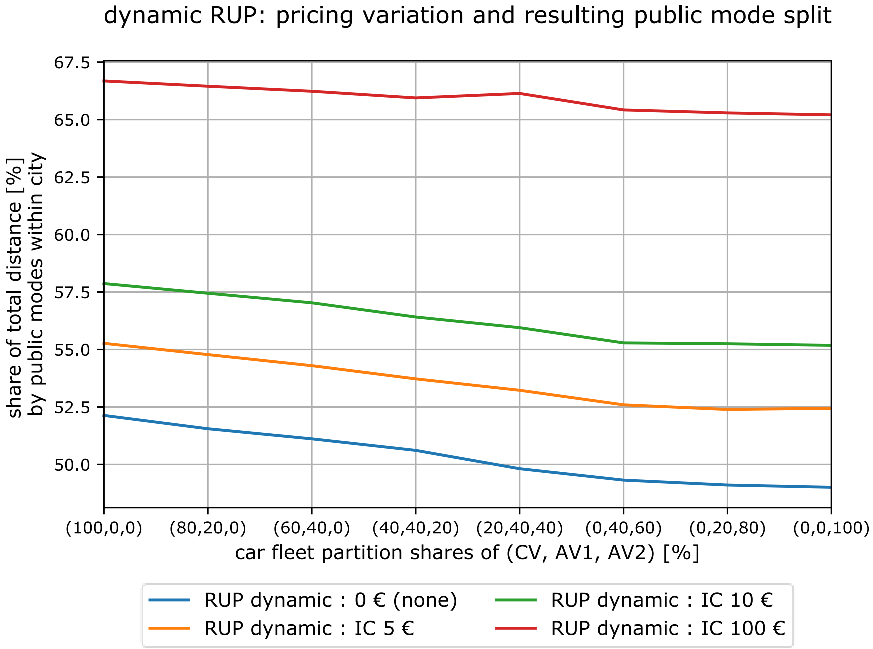


Figure 4.29: Dynamic RUP - public modes' distance share within the city limits for the static RUP scenarios at increasing pricing levels, shown along an assumed evolution of increasing car fleet automation along the horizontal axis.

Marginal utility of money (mUoM)

To investigate effects on the public transport mode share by distance under the assumption of changed monetary value, simulations were made to assume monetary value shifts of +/- 5%, which cause the simulated agents to reconsider their mobility behaviour with respect to the monetary cost shares (as opposed to time-costs).

Figure 4.30 shows the consistent decrease of the public mode split for increasing automation levels. The different values for mUoM behave according to expectation, where an increase in the felt value of money (mUoM = 1.05) causes an increase in the cost-efficient public mode utilization.

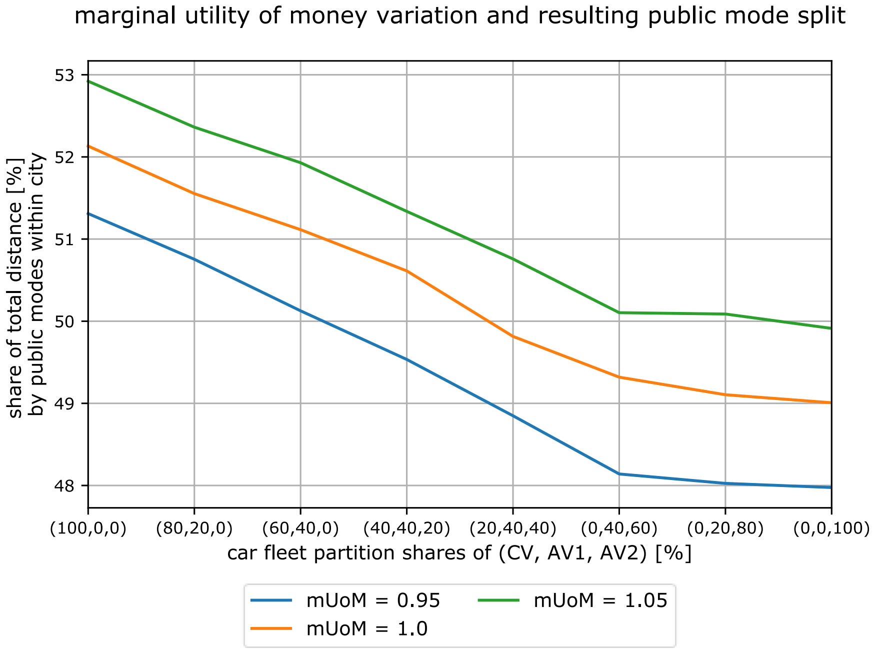


Figure 4.30:No RUP scenarios (0 € toll) - public modes' distance share within the city limits for the no RUP scenarios and varied levels of the marginal utility of money, shown for an assumed evolution of increasing car fleet automation along the x-axis.

4.3.2 Results from system dynamics

System dynamics model was used to forecast changes in modal split due to the introduction of AVs, and additionally with several policy interventions including parking space regulations, parking pricing, and provision of automated ride sharing service. The model description is detailed under section 3.3.1. The following results (Figure 4.31) on modal split were obtained for public transport based on distance travelled.

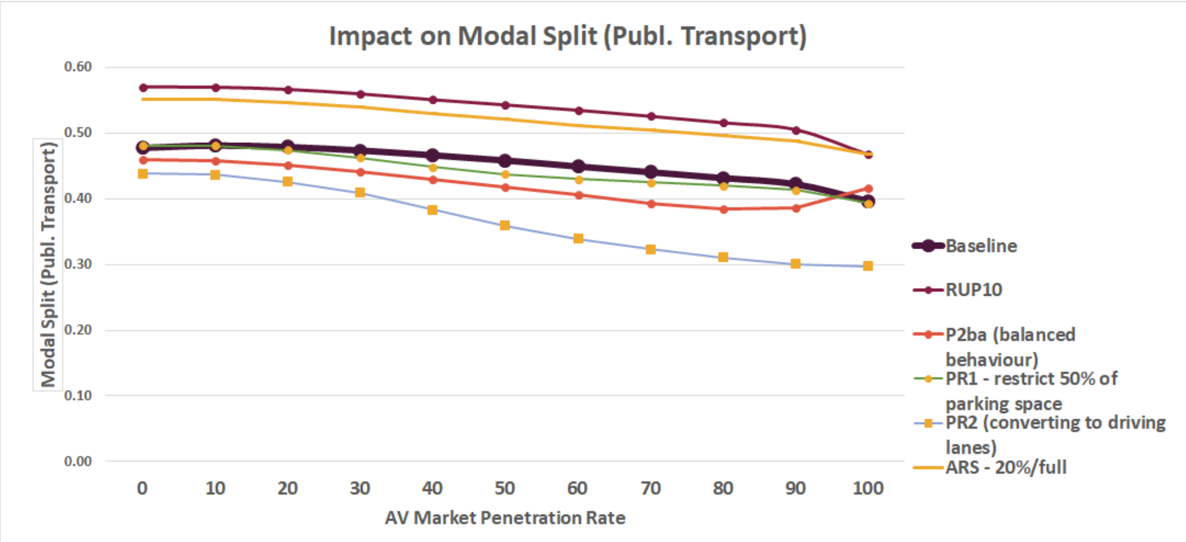


Figure 4.31: Impact of automation (baseline) and different policy interventions on modal split using public transport (RUP=road use pricing, P2ba=Parking behaviours under balanced scenario, PR1=remove 50% on-street parking spaces, PR2=replacing on-street parking with driving lane, ARS-20% full= Automated ride sharing with 20% demand and 100% willingness to share).

The modal split is determined as share by distance of trips carried out using that transport mode, shown as a fraction of the total distance travelled in any available mode.

Percentage of public transport usage is estimated to slowly decrease with increasing MPR of AVs with maximum decrease (almost 10%) at full fleet penetration. This can be foreseen as a consequence that increase in access, convenience, and affordability of private automated cars with time and increasing automated fleet.

Implementation of road-use pricing would likely increase modal share in public transport as compared to the baseline curve, as evident through the results presented in Figure 4.31, in order to avoid paying toll. However, the decrease in percentage would be observed consistent with the baseline curve due to the aforementioned reasons.

Policy on parking space regulations can have a strong impact on changes in modal split as also found in the SD model results. For example, replacing on-street parking with driving lanes would encourage more vehicles on the roads potentially reducing share of public transport users with increasing MPR; however, becoming almost insensitive at around 80% fleet penetration. Removing 50% on-street parking was found to have a marginal impact on modal shift to public transport.

With regard to parking pricing policies, a balanced strategy (includes proportions of all parking options) was included in SD model as this was found to be potentially the best strategy in terms of its impacts on traffic operations, as also indicated under section 4.1.2.Under balanced parking strategy, a slight reduction in public transport modal split was estimated with increasing MPR with a slight increase at full MPR scenario. This may be attributed to increased congestion at full fleet penetration with such parking policy.

The increased modal share in public transport for Automated ride sharing service is due to the fact that this new mode is included in public transport. But, similar to other SUCs, it can likely decrease at or near full MPR due to increased access, convenience, and affordability to private automated passenger cars.

4.3.3 Results from Delphi

4.3.3.1 Road use pricing

According to the 1st round replies, all city toll scenarios will positively affect modal split using public transport (Figure 4.32). More precisely, the introduction of static city toll will affect the most the studied impact the most, leading to an increase of 22,4% for lower AVs market penetration rates and 16,9% for 100% AVs market penetration rate. Dynamic city toll will lead to an increase of 16,7 in the short term and 8,8% in the long term. Empty km pricing will increase the least (4,2%-8%) modal split using public transport. On the other hand, the introduction of AVs in the urban environment will reduce (28,6%) modal split using public transport.

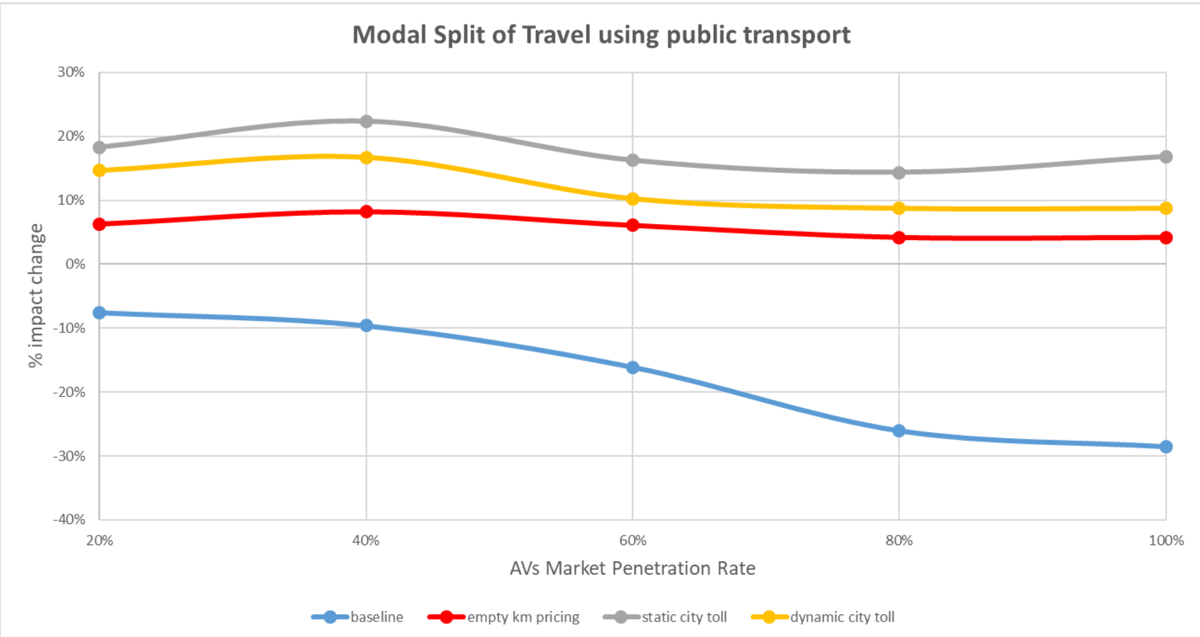


Figure 4.32: 1st round Delphi modal split using public transport results for the city toll scenarios

The majority of the 2nd round participants stated that they definitely (14%) or moderately (72%) agree with the 1st round curves of the city toll scenarios (Figure 4.33). One expert slightly agreed with the curves and suggested that the city toll scenarios will also reduce (5%) modal split using public transport. All experts definitely (43%) or moderately (57%) agreed with the 1st round results for the baseline scenario.

Figure 4.33: 2nd round Delphi modal split using public transport for baseline and empty km pricing scenarios

4.3.3.2 Provision of dedicated lanes on urban highways

According to the 1st round replies, all scenarios will negatively affect modal split using public transport since they all increase the use of privately owned vehicles. More precisely, the introduction of AVs in the urban environment will reduce (24,6%) the most modal split using public transport. The introduction of AV dedicated lanes on the outermost motorway lane, innermost motorway lane and outermost motorway lane and A-road, will have the same impact on modal split using public transport in the long term, reaching a reduction of 20%.

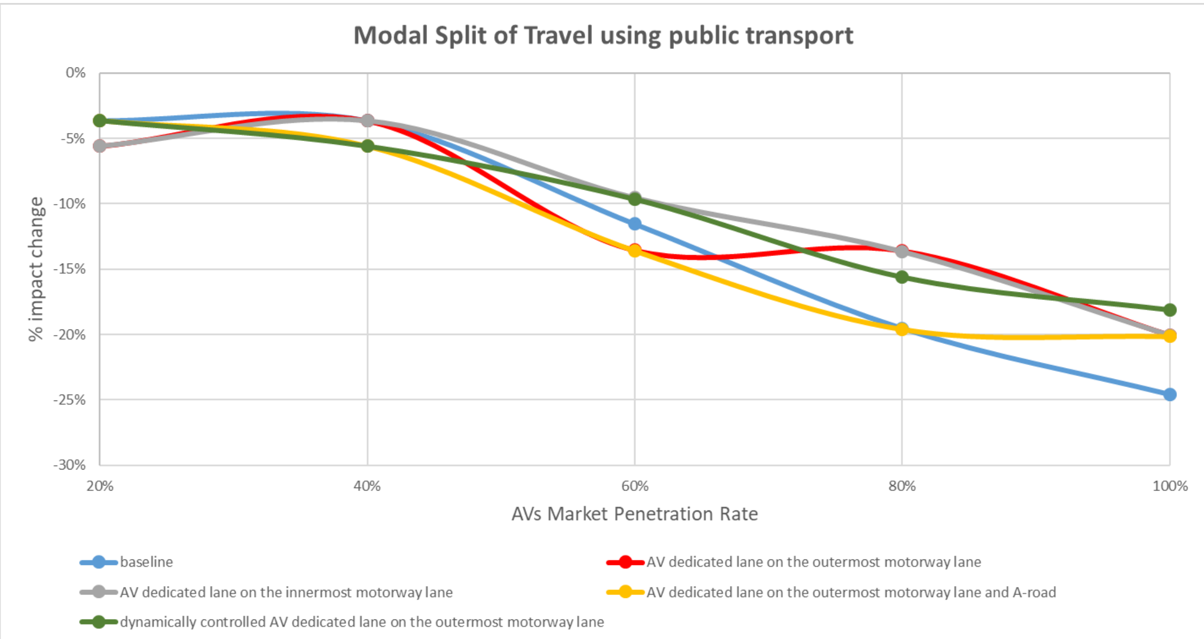


Figure 4.34: 1st round Delphi modal split using public transport results for the AV dedicated lanes scenarios

In the second Delphi round, all experts definitely (33%) or moderately (67%) agreed with the resulted trend for the baseline scenario (Figure 4.35). Additionally, the majority of 2nd round participants stated that they definitely (34%) or moderately (33%) agreed with the curves of the AV dedicated lanes scenarios. Some experts (33%) suggested that the AV dedicated lanes scenarios will not significantly affect the modal split using public transport.

Figure 4.35: 2nd round Delphi modal split using public transport for baseline and innermost motorway lane scenarios

4.3.3.3 Parking price policies

According to the 1st round replies CAVs parking outside is the only intervention that will increase modal split using public transport reaching 10,8% for 60% AVs market penetration rate (Figure 4.36). All other proposed scenarios will negatively affect modal split using public transport. More precisely, the baseline scenario will lead to a 17,6% reduction in the long term. Regarding the parking behaviour scenarios, experts suggested that modal split using public transport will be reduced in the long term by 14,2% after the introduction of CAVs parking around behaviour, or by 14,7% after the introduction of CAVs parking inside or returning to origin.

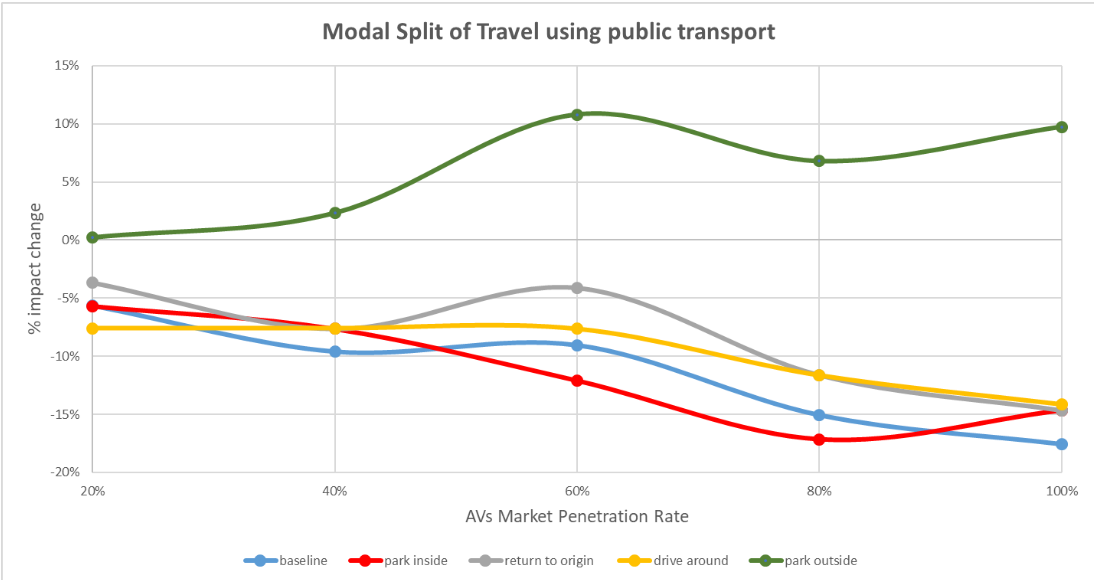


Figure 4.36: 1st round Delphi modal split using public transport results for the CAV price policies behaviour scenarios

The majority of the 2nd round participants stated that they agree definitely (50%) or moderately (17%-33%) with the resulted trends (Figure 4.37). Some experts (33%) suggested that CAVs parking outside behaviour will also affect negatively modal split using public transport, leading to an average reduction of about 20%.

Figure 4.37: 2nd round Delphi modal split public transport results for baseline and CAVs parking outside scenarios

4.3.3.4 Parking space regulations

According to the 1st round replies, replacing on-street parking space with space for public use will increase the most modal split using public transport reaching 30% for 100% AVs market penetration rate (Figure 4.38). Replacing on-street parking space with driving lanes or with pick-up/drop-off parking space will both lead to an increase of modal split using public transport, reaching in the long term 4% and 9,3% respectively. Regarding the baseline scenario, experts suggested that modal split using active travel will reduce 6%-10% regardless of the AVs market penetration rate.

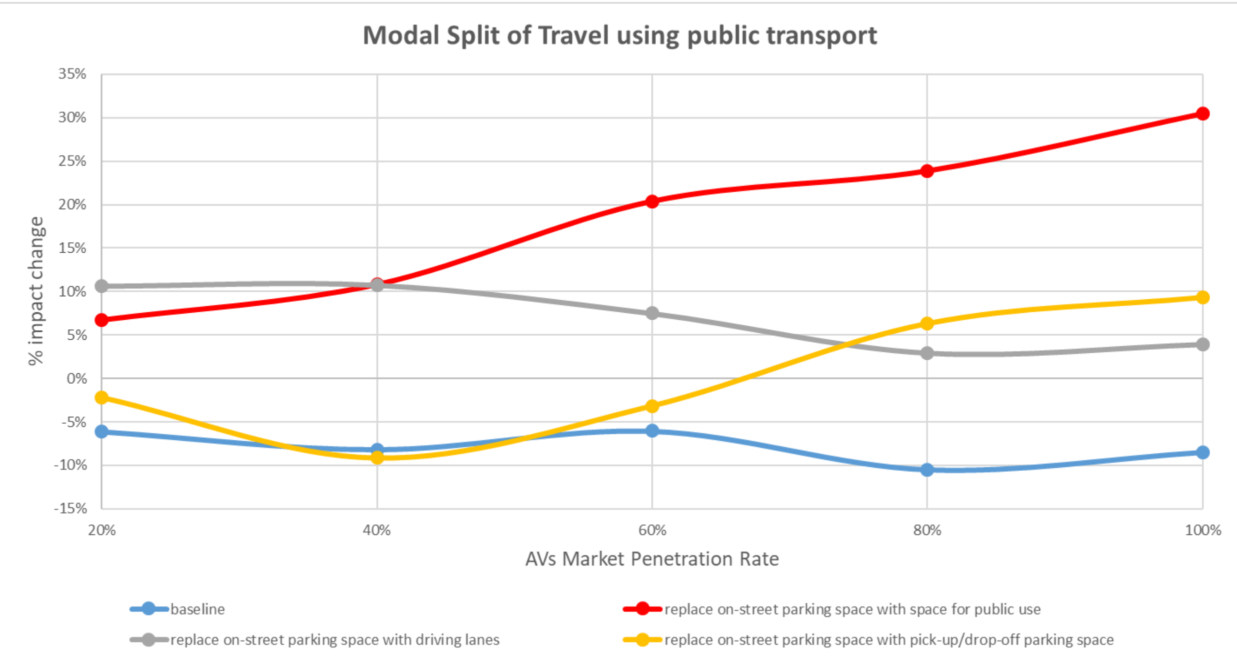


Figure 4.38: 1st round Delphi modal split using public transport results for parking space regulation scenarios

All of the 2nd round participants stated that they agree definitely (60%-100%) or moderately (0%-40%) with the resulted trends (Figure 4.39). One expert suggested that all the studied scenarios will lead to a reduction of about 30% in modal split using public transport.

Figure 4.39: 2nd round Delphi modal split using public transport results for replacing on-street parking space with pick-up/drop-off and driving lanes

4.3.3.5 Automated ride sharing

According to experts, the baseline scenario (no intervention) will reduce (19,1%) modal split using public transport in the long term when AVs market penetration rates are higher (Figure 4.40). The introduction of automated ridesharing will increase modal split using public transport especially in the short term, reaching 12% for 40% AVs market penetration rate.

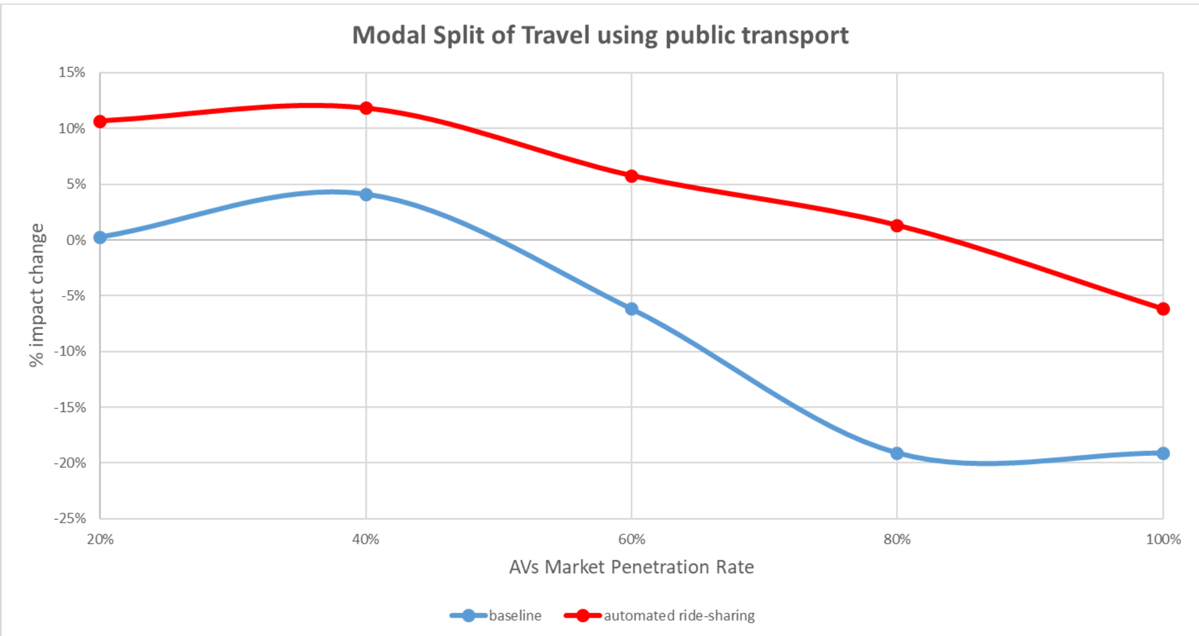


Figure 4.40 1st round Delphi modal split using public transport results for the automated ridesharing scenarios

The majority of 2nd round participants stated that they definitely (17%) or moderately (50%) agreed with the resulted 1st round trends for the baseline scenario (Figure 4.41). Some experts (33%) stated that the baseline scenario will have a general negative impact on modal split using public transport of about 10%. According to 50% of automated ridesharing will in fact decrease modal split using public transport by 10%.

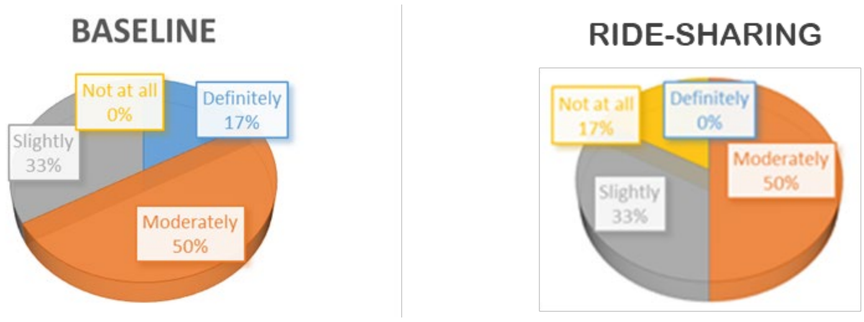


Figure 4.41 2nd round Delphi modal split using public transport results for baseline scenario (automated ridesharing)

4.3.3.6 Green Light Optimal Speed Advisory (GLOSA)

According to experts, the baseline scenario (no intervention) will reduce (19,1%) modal split using public transport in the long term when AVs market penetration rates are higher (Figure 4.42). GLOSA will negatively affect modal split using public transport and for 100% AVs market penetration rate, this scenario will reduce by 9,6% the studied impact.

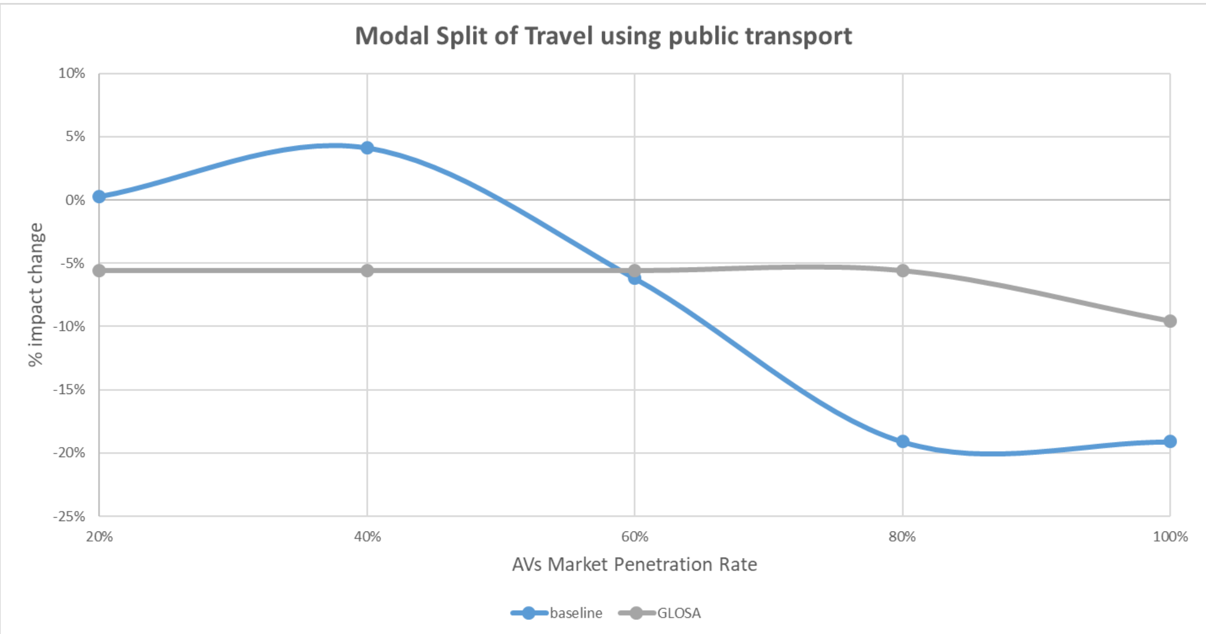


Figure 4.42: 1st round Delphi modal split using public transport results for GLOSA scenarios

The majority of 2nd round participants stated that they definitely (17%) or moderately (50%) agreed with the resulting 1st round trends for the baseline scenario (Figure 4.43). Two experts (33%) stated that the baseline scenario will have a general negative impact on modal split using public transport of about 10%. According to 50% of experts GLOSA will not at all affect the studied impact.

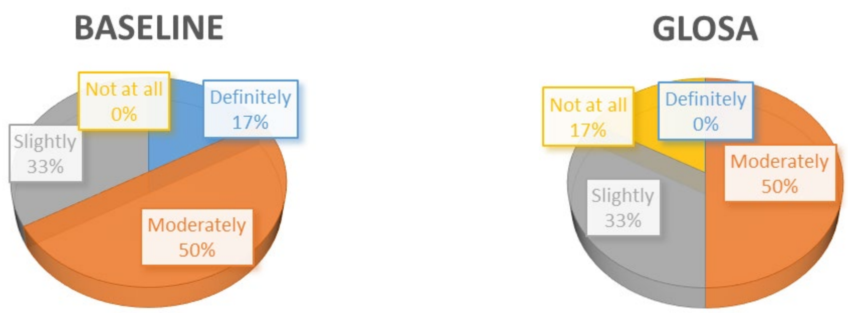


Figure 4.43: 2nd round Delphi modal split using public transport results for baseline and GLOSA scenarios

4.4 Modal split using active travel

The impact of automation on modal split using active travel (% of trip distance made using active transportation (walking, cycling)) has been estimated using the mesoscopic simulation, system dynamics and Delphi methods.

4.4.1 Results from mesoscopic simulation – Road use pricing

For the mesoscopic simulation, the modal split was determined as the share by distance of trips carried out using the main transport mode (as defined above) as a fraction of the total distance travelled in any available mode within the city boundaries (being the outline of the blue domain – the investigation perimeter in Figure 3.16). The RUP measure only affects part of that area (i.e., the inner-city region), which has to be taken into account.

The transport mode of a trip is classified according to its *longest distance mode* (ldm), meaning the largest part of the overall distance has been covered by using a bicycle, for example. No matter what the ldm of one specific trip may be, they mostly are composed of stages of different modes, including at least access and egress walking to and from other modes of transport.

Based on the mode classification of each trip it is apparent, that the modal split for active transport as defined here will preferably concern shorter trips, as opposed to the modal split for public transport described in section 4.3.1.

The intent of implementing RUP for a chosen area is regional attenuation of the tolled modes of transport, which, in the presented scenarios are the conventional and automated passenger cars. Reduction in the use of tolled modes impacts the overall characteristics of the changed population of mobile agents and their trips between locations of activity.

Static RUP

Impact results of examining the effects on the active transport mode share by distance for different static road use pricing schemes (as defined in section 3.2.3) are displayed in

Figure 4.44. They show the simulated mobility behaviour when the entrance fee into the tolling area of the inner city (IC) is increased.

The expectable effects of increasing availability of automated cars on the active travel mode split are rather small under the presented scenario assumptions. This is documented in Figure 4.44, where most static RUP scenarios show a mere 0.5 % decline in active mode split when going from 0 % to 100 % automation level.

A change from the current no-RUP scenario to the prohibitive tolling (100 €) is able to raise the active mobility split by about 4 %. It is noteworthy however, that this increase of an impact defined for the whole city area is caused by the regionally limited implementation of RUP within the inner city alone.

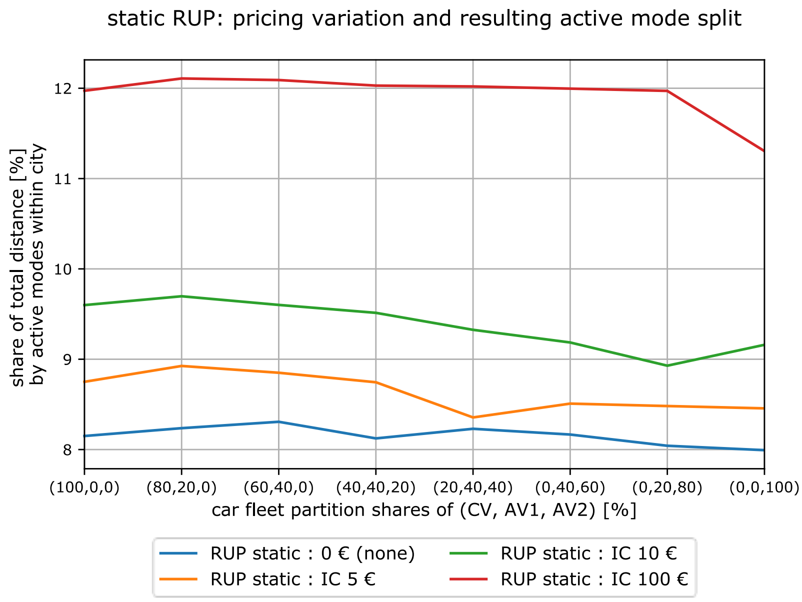


Figure 4.44: Static RUP - active modes' distance share within the city limits for the static RUP scenarios at increasing pricing levels, shown along an assumed evolution of increasing car fleet automation along the horizontal axis.

Dynamic RUP

Effects on the active transport mode share by distance for different dynamic road use pricing schemes (as defined in section 3.2.3) are shown in Figure 4.45. The simulated mobility behaviour describes the situations when the fee per 7 km of distance driven inside the tolling area of the inner city (IC) is increased in steps equivalent to the prices defined before. In these scenarios not all vehicles entering the tolling area will be charged equally high fees, as some of the agents only cross into the IC briefly to soon leave again, therefore only amounting to low tolling costs.

The active mode split shows a minimal decline (<= 0.5 %) in Figure 4.45 when following each RUP scenario from no automation to full automation. Comparable to the static RUP case the maximum possible impact change from no-RUP to prohibitive RUP amounts to +4 %. And to restate the above: This increase of an impact defined for the whole city area is caused by the regionally limited implementation of RUP within the inner city alone.

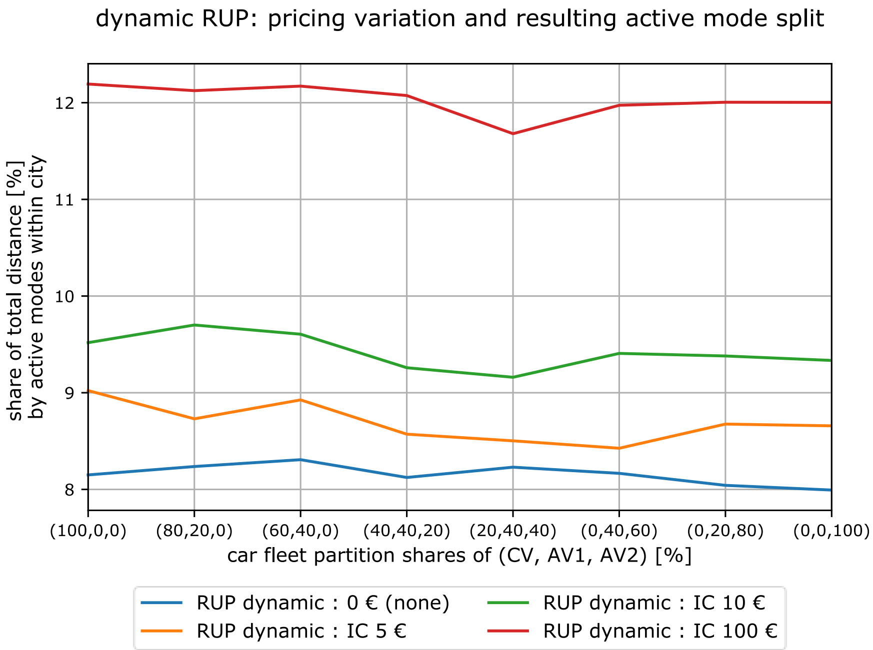


Figure 4.45: Dynamic RUP - active modes' distance share within the city limits for the static RUP scenarios at increasing pricing levels, shown along an assumed evolution of increasing car fleet automation along the horizontal axis.

Marginal utility of money (mUoM)

To investigate effects on the active transport mode share by distance under the assumption of changed monetary value, simulations were made to assume monetary value shifts of +/- 5%, which cause the simulated agents to reconsider their mobility behaviour with respect to the monetary cost shares (as opposed to time-costs).

Under variation of the mUoM the active mode share changes are documented in Figure 4.46. The overall trend shows a small – 0.5 % change for increasing automation levels. Higher valued of monetary costs (mUoM = 1.05) instils a higher share of active mobility. The data in that case does exhibit some fluctuations arising from randomness in the optimization process, but these fluctuations amount to only 0.15 % of the impact value itself.

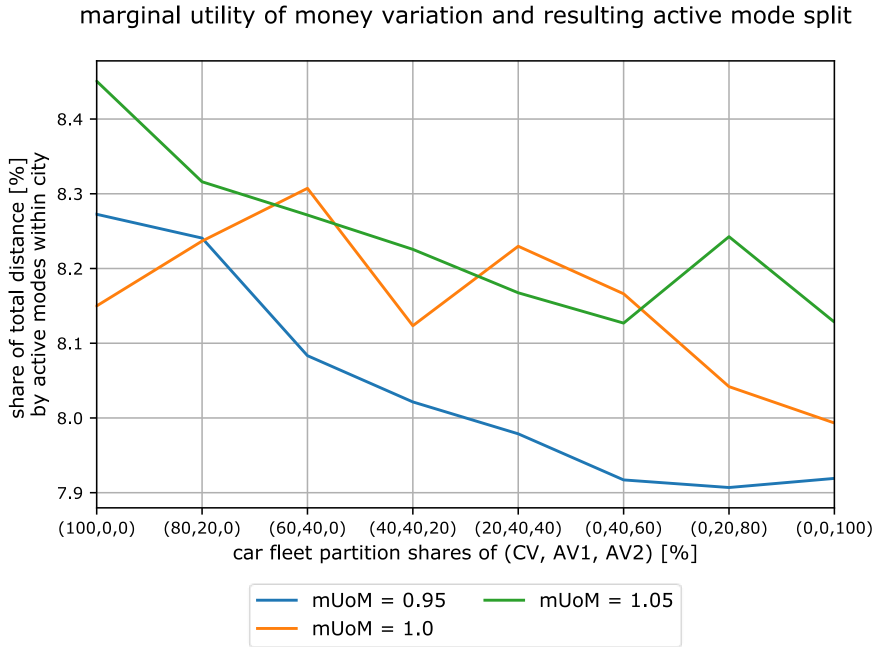


Figure 4.46: No RUP scenarios (0 € toll) - active modes' distance share within the city limits for the no RUP scenarios and varied levels of the marginal utility of money, shown for an assumed evolution of increasing car fleet automation along the x-axis.

4.4.2 Results from system dynamics

Modal split of active travel was also predicted using a system dynamics model based on the impact of increasing automation, and other policy interventions analysed in this deliverable including road use pricing, parking behaviours due to pricing policies, parking space regulations, and automated ride sharing services. The results are presented through the plot in Figure 4.47.

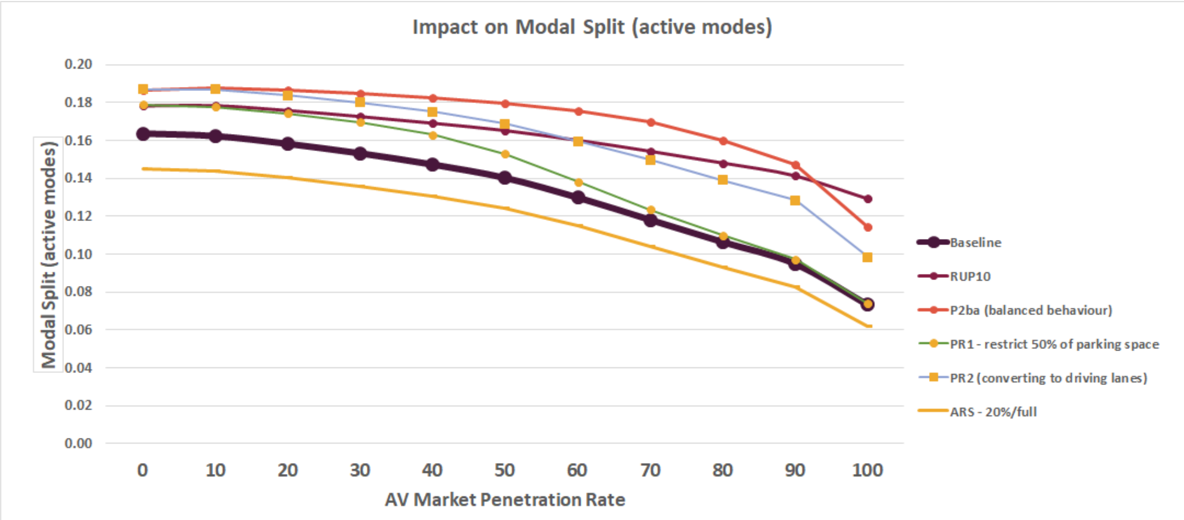


Figure 4.47: Impact of automation and various policy interventions on modal split using active travel (RUP=road use pricing, P2ba=Parking behaviours under balanced scenario, PR1=remove 50% on-street parking spaces, PR2=replacing on-street parking with driving lane, ARS-20% full= Automated ride sharing with 20% demand and 100% willingness to share)

The modal split is determined as share by distance of trips carried out using that transport mode, shown as a fraction of the total distance travelled in any available mode.

With respect to baseline scenario (increasing automation only), active travel is predicted to decrease with increasing MPR of AVs in the transport system. This trend was also found to be common under implementation of all sub-use cases (policy interventions). The relative impact compared to the baseline, however, was found to be diverse.

Analysing modal split (active modes) curves (Figure 4.47) under different policy interventions, the results indicated significant increase in active travel due to road use pricing and balanced parking behaviours, as compared to the baseline results. This trend can be expected as such policies involving some sort of price would likely impact motorized travel and influence people to prefer use of active modes. Whereas parking price policies showed higher increase for medium automation levels, road use pricing showed a higher effect for 100% AV penetration rate.

Automated ride sharing services are likely to negatively impact active travel with respect to baseline due to providing pick-ups and drop-offs closest to the origins and destinations of passengers.

Finally, the results indicated a slight increase in active travel due to replacing on-street parking with driving lanes/cycling lanes, whereas just removing half of the parking spaces was found to increase active travel up to 70% MPR and become insensitive with further increase in the fleet penetration.

4.4.3 Results from Delphi

4.4.3.1 Road use price

According to experts, the introduction of AVs in the urban environment will negatively affect modal split using active travel leading to a reduction of 20,1% (Figure 4.48). Regarding the city toll scenarios, empty km pricing and static city toll will both increase modal split using active travel by 4,3% and 12,9% respectively, in the long term. The dynamic city toll scenario will reduce (6,8%) modal split by using active travel, but all the negative impact is minimized in the long term, leading to a slight increase of 2,3% for 100% AVs market penetration rate.

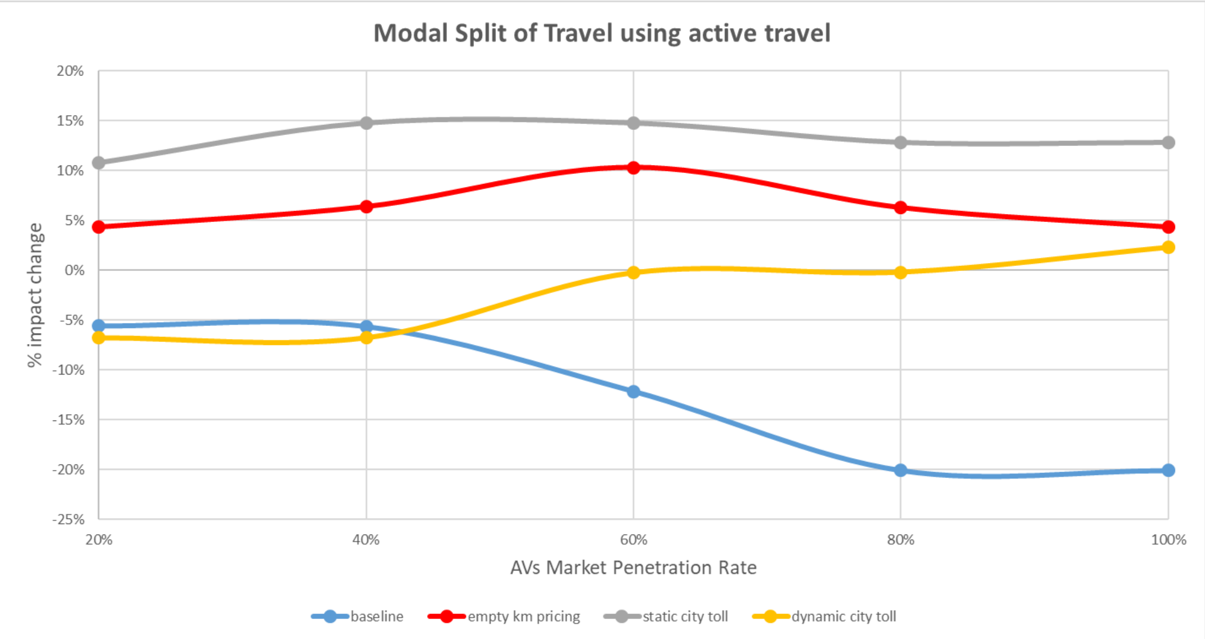


Figure 4.48: 1st round Delphi modal split using active travel results for the city toll scenarios

The majority of the 2nd round participants stated that they definitely (14%) or moderately (72%) agreed with the 1st round curves of the empty km pricing and dynamic city toll scenarios (Figure 4.49). One expert (14%) slightly agreed with the curves and suggested that both scenarios will increase modal split using active travel. All experts definitely (14%-43%) or moderately (57-72%) agreed with the 1st round results for the baseline scenario and the static city toll scenario.

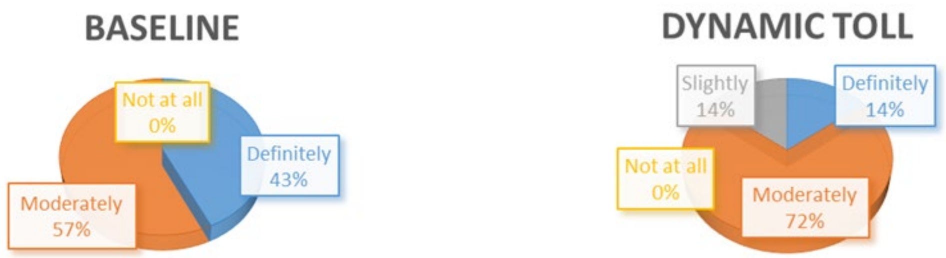


Figure 4.49: 2nd round Delphi modal split using active travel results for baseline and dynamic city toll

4.4.3.2 Provision of dedicated lanes on urban highways

According to experts, the introduction of AVs in the urban environment will negatively affect modal split using active travel leading to a reduction of 16% (Figure 4.50). The AVs dedicated lanes scenarios will not significantly affect the studied impact. The scenario of an AV dedicated lane on the outermost motorway lane, as well as on the innermost motorway lane will mostly affect modal split using active travel, among the other AV dedicated lane scenarios, reaching a reduction of 10%.

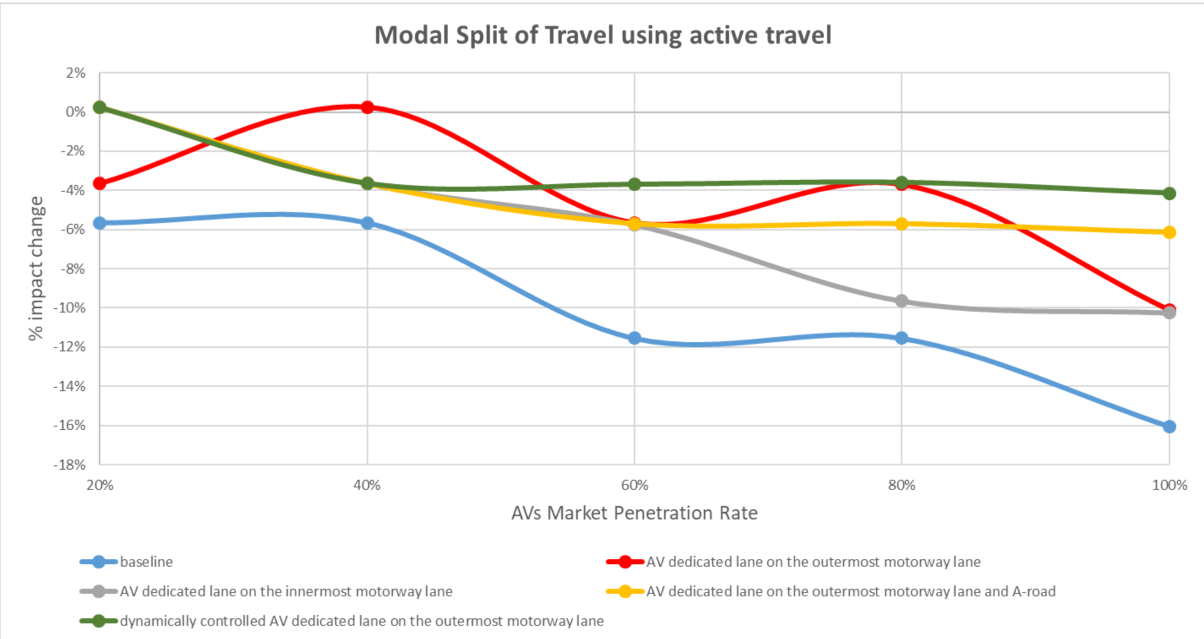


Figure 4.50 1st round Delphi modal split using active travel results for the AV dedicated lanes scenarios

The majority of the 2nd round participants stated that they agree moderately (67%) with the resulted trends for the AV dedicated lane scenarios (Figure 4.51). The majority of experts stated that they slightly (33%) or not at all (33%) agree with the baseline scenario curve and suggest a more linear decrease of modal split using after travel in the long term.

Figure 4.51: 2nd round Delphi modal split using active travel results for baseline and AV dedicated lane on the outermost motorway lane

4.4.3.3 Parking price policies

According to experts, the introduction of AVs in the urban environment will negatively affect modal split using active travel leading to a reduction of 39,1% (Figure 4.52). CAVs parking outside the city centre will not significantly impact modal split using active travel. The other CAVs parking behaviours scenarios will reduce modal split using active travel, and particularly CAVs driving around will lead to a reduction of 22,1% in the long term. CAVs parking inside and returning to origin will reduce modal split using active travel by 14,6% and 11,7% respectively.

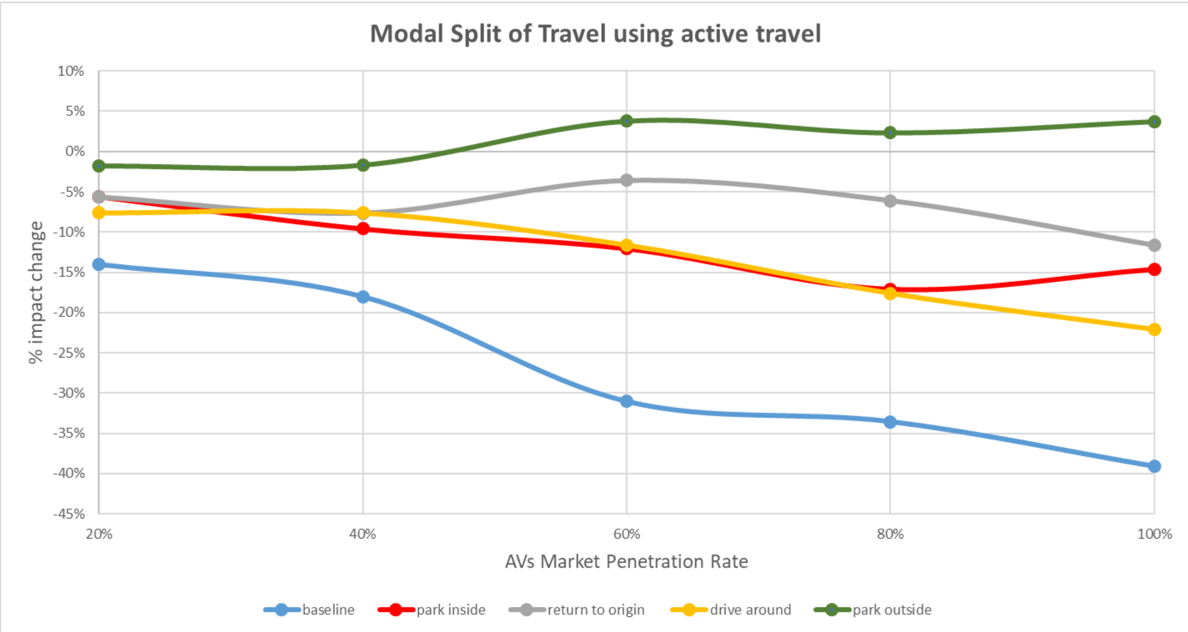


Figure 4.52 1st round Delphi modal split using active travel results for the CAV parking price policies scenarios

The majority of the 2nd round participants stated that they agreed definitely (50%) or moderately (33%) with the resulted trends (Figure 4.53). One expert (17%) suggested that CAVs parking outside behaviour should also lead negatively affect modal split using public transport, leading to an average reduction of about 10%.

Figure 4.53: 2nd round Delphi modal split using active travel results for CAVs return to origin and parking outside scenarios

4.4.3.4 Parking space regulations

According to experts, all parking regulations scenarios will increase modal split using active travel (Figure 4.54). Since finding a parking spot will be more difficult when reducing on-street parking space, people will tend to use more active travel especially for near destinations. More precisely, replacing on-street parking space with space for public use, with driving lanes or with pick-up/drop-off parking space, will increase modal split using active travel by 31,5%, 9,3% and 8,3% respectively. The baseline scenario will tend to have a negative impact on modal split using active travel especially as the AVs market penetration rate increases, reaching -28,1%, for 100% AVs market penetration rate. This reduction of modal split using active travel may be explained by the general perception that introduction of AVs will improve door-to-door travel.

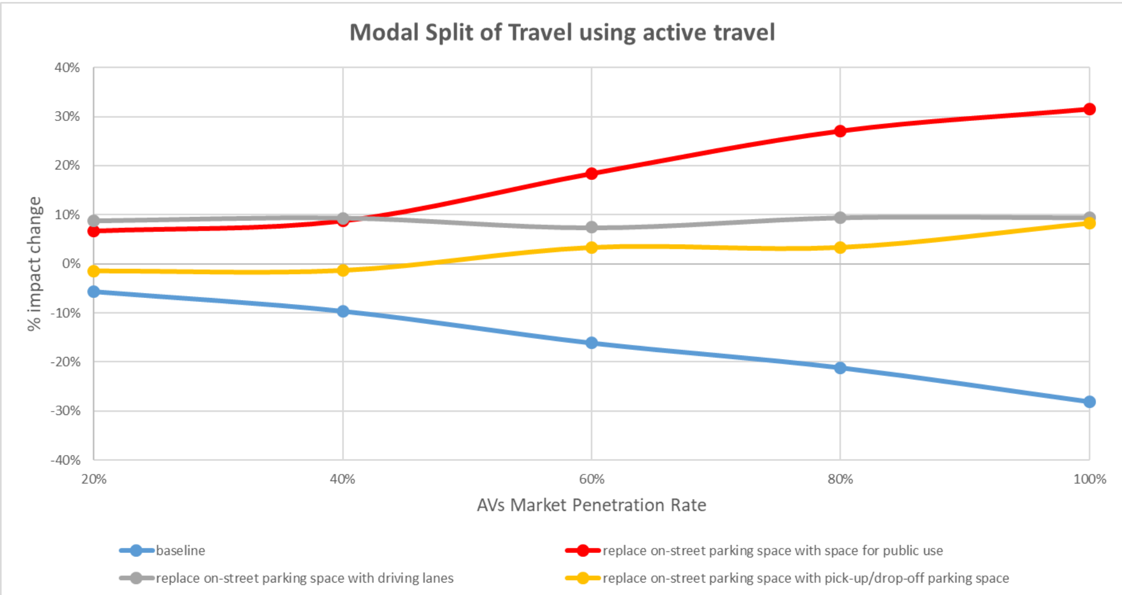


Figure 4.54 1st round Delphi modal split using active travel results for parking space regulations scenarios

In the second Delphi round, experts stated that they agreed definitely (60%-100%) or moderately (0%-40%) with the curves of the 1st round (Figure 4.55).

Figure 4.55: 2nd round Delphi modal split using active travel results for baseline and replacing on-street parking space with pick-up/drop-off parking space scenarios

4.4.3.5 Automated ride sharing

According to experts, the introduction of AVs in the urban environment as well as the automated ridesharing will increase modal split using active travel leading to an increase of 5,5% in the long term (Figure 4.56). The baseline scenario presents a peak at around 80% of AVs market penetration rate, where the increase of modal split using active travel reaches 17%.

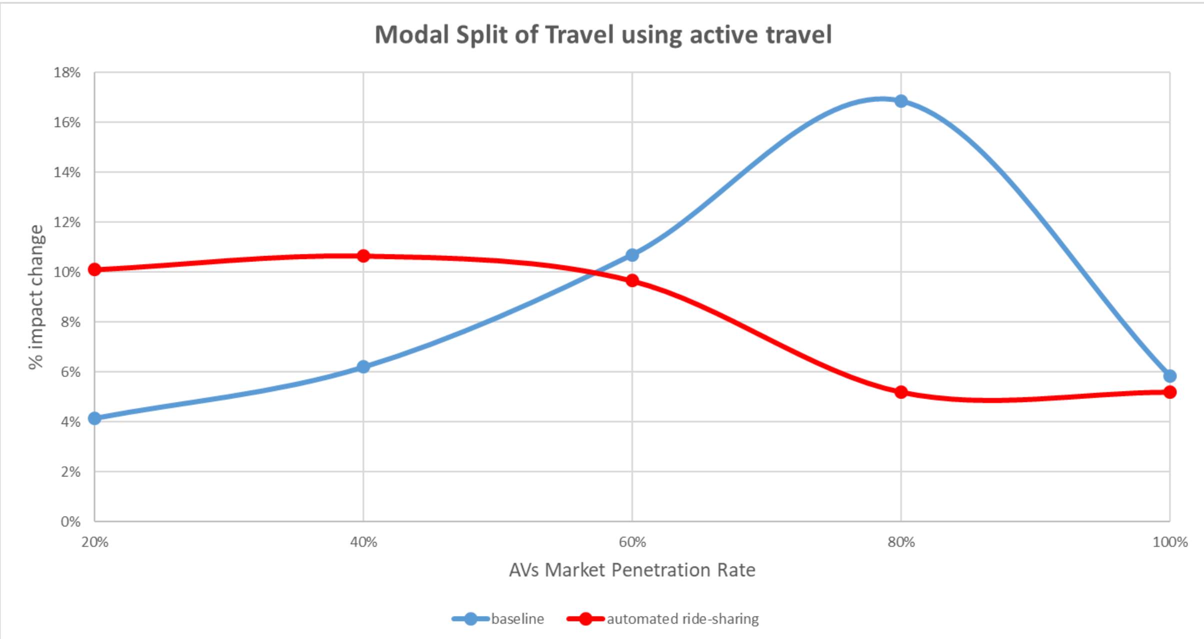


Figure 4.56: 1st round Delphi modal split results using active travel results for the automated ridesharing and GLOSA scenarios

Half of the 2nd round participants stated that they definitely (17%) or moderately (33%-50%) agreed with the resulted 1st round trends (Figure 4.57). According to 50% of experts, automated ridesharing and the baseline scenario will both decrease modal split using active travel by 10%.

Figure 4.57: 2nd round Delphi modal split results using active travel results for baseline and automated ridesharing scenarios

4.4.3.6 Green Light Optimal Speed Advisory (GLOSA)

According to experts, the introduction of AVs in the urban environment will increase modal split using active travel, leading to an increase of 5,5% in the long term. The baseline scenario presents a peak at around 80% of AVs market penetration rate, where the increase of modal split using active travel reaches 17%. Regarding the GLOSA scenario, experts suggested a general reduction (5,6%) of modal split using active travel regardless of the AVs market penetration rate.

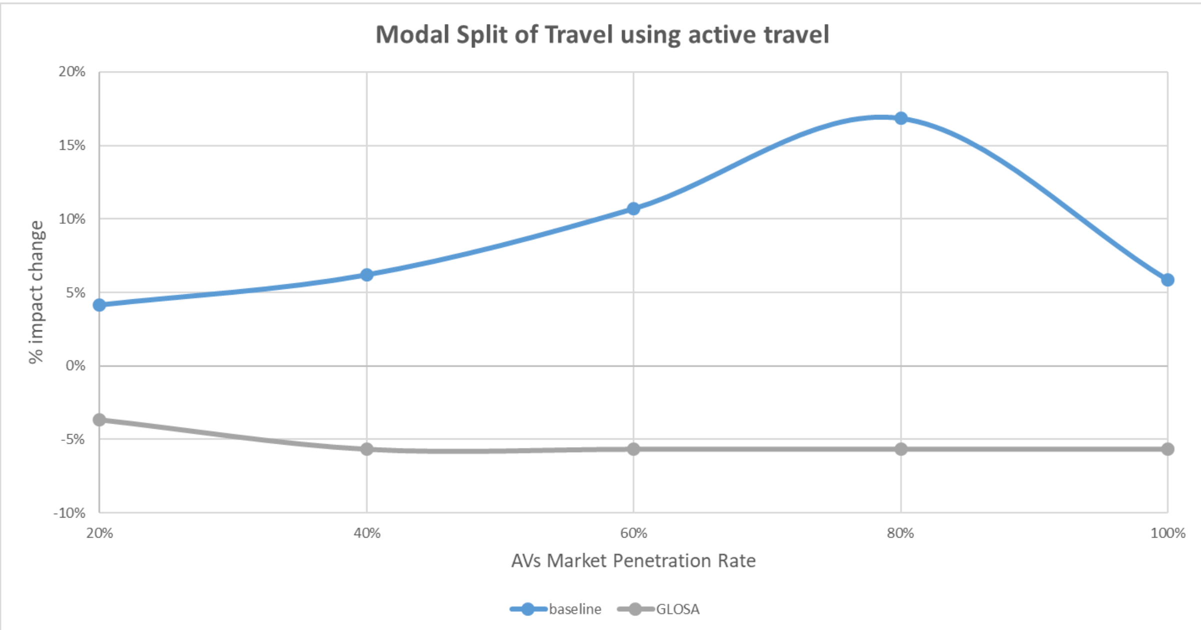


Figure 4.58: 1st round Delphi modal split using active travel results for and GLOSA scenarios

According to 50% of experts, GLOSA will not at all affect the studied impact and the baseline scenario will decrease modal split using active travel by -10%.

Figure 4.59: 2nd round Delphi modal split results using active travel results for baseline and GLOSA scenarios

4.5 Shared mobility rate

The impact of automation on shared mobility rate (% of trips made sharing a vehicle with others) has been estimated by using Delphi method.

4.5.1 Road use pricing

According to experts, shared mobility rates will be increased after the introduction of AVs in the baseline scenario, as well as after the introduction of city tolls. More precisely, for 100% AVs market penetration rate shared mobility rate will increase by 25,9% for the baseline scenario. All city toll scenarios increase shared mobility rate in the long term. The introduction of dynamic city toll will mostly increase (24,8%) shared mobility rate, among the other city toll scenarios.

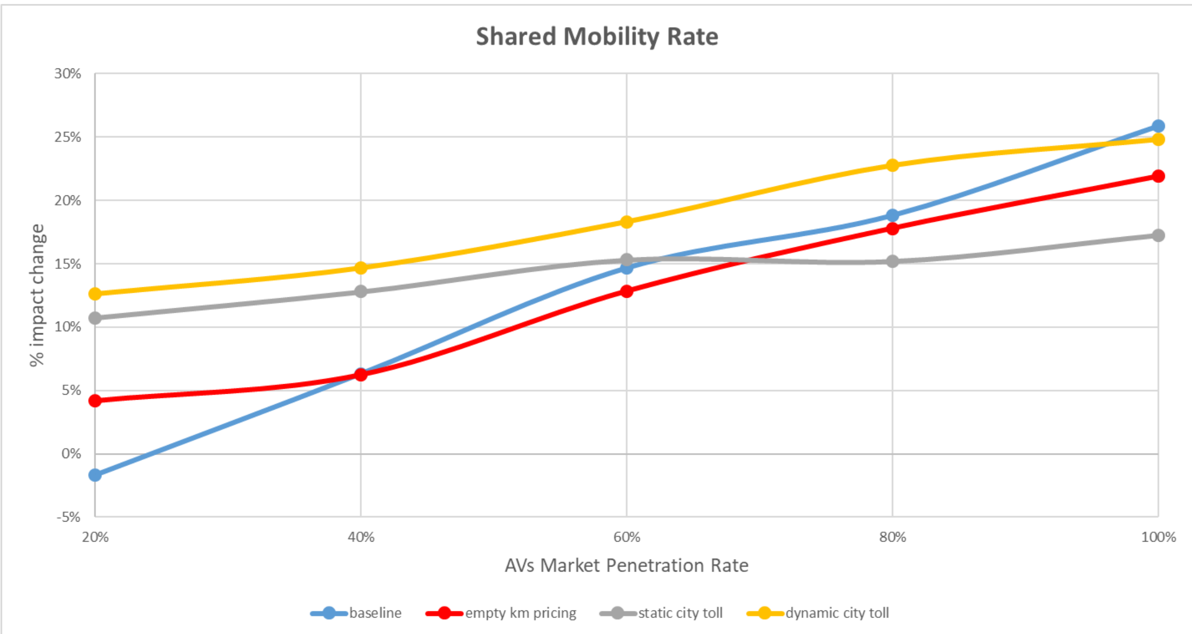


Figure 4.60: 1st round Delphi shared mobility rate results for the city toll scenarios

The majority of the 2nd round participants stated that they definitely (28%-43%) or moderately (43%) agreed with the 1st round curves. Some experts (14%-29%) slightly agreed with the curves and suggested that all scenarios will increase shared mobility rate at an average of 5% to 10%.

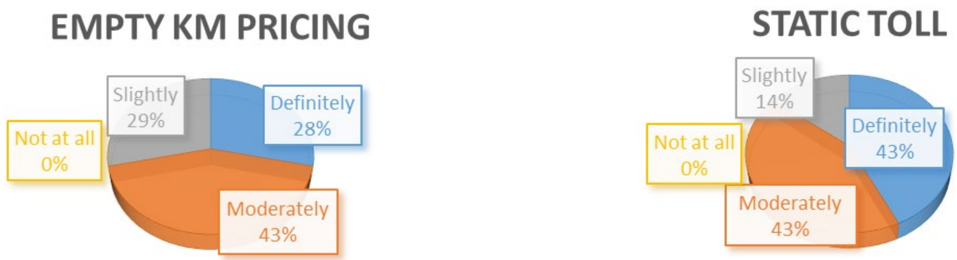


Figure 4.61: 2nd round Delphi shared mobility rate results for empty km pricing and static city toll

4.5.2 Provision of dedicated lanes on urban highways

According to experts, shared mobility rates will be increased after the introduction of AVs in the baseline scenario, as well as after the implementation of the AV dedicated lanes (Figure 4.62). More precisely, for 100% AVs market penetration rate shared mobility rate will increase by 35,5% for the baseline scenario. AV dedicated lane scenarios present some fluctuations, but all increase shared mobility rates in the long term. The introduction of dynamically controlled AV dedicated lane on the outermost motorway lane will mostly increase (25,4%) shared mobility rate, among the other AV dedicated lane scenarios.

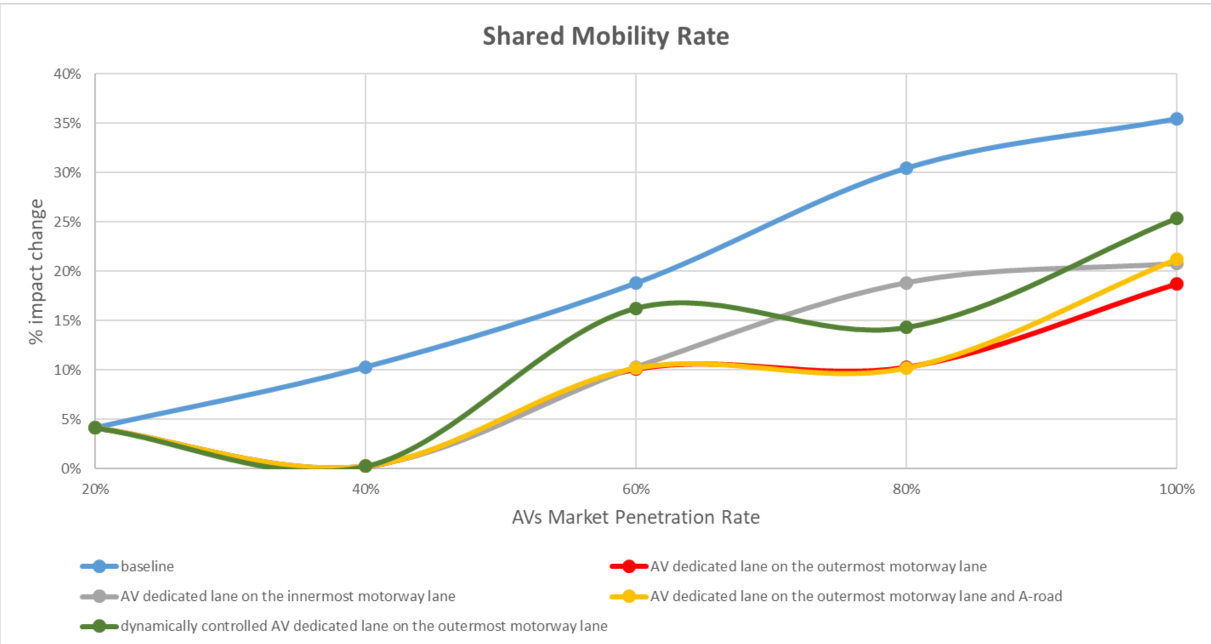


Figure 4.62: 1st round Delphi shared mobility rate results for the AV dedicated lanes scenarios

In the 2nd round of questionnaires, the participants agreed definitely (33%) or moderately (67%) with the first-round curves (Figure 4.63). Two experts (33%) stated that they do not at all agree with the dynamically controlled AV dedicated lane curve and suggested that a curve with less fluctuations would be more reasonable.

Figure 4.63: 2nd round Delphi shared mobility rate results for baseline and dynamically controlled AV dedicated lane

4.5.3 Parking price policies

According to experts, shared mobility rates will be increased after the introduction of AVs in the baseline scenario, as well as after the implementation of the CAVs parking behaviours (Figure 4.64). More precisely, for 100% AVs market penetration rate shared mobility rate will increase by 28,5% for the baseline scenario. CAVs parking inside, returning to origin, driving around or parking outside will increase the studied impact by 30,4%, 20,9%, 31,9% and 16,9% respectively for 100% AVs market penetration rate.

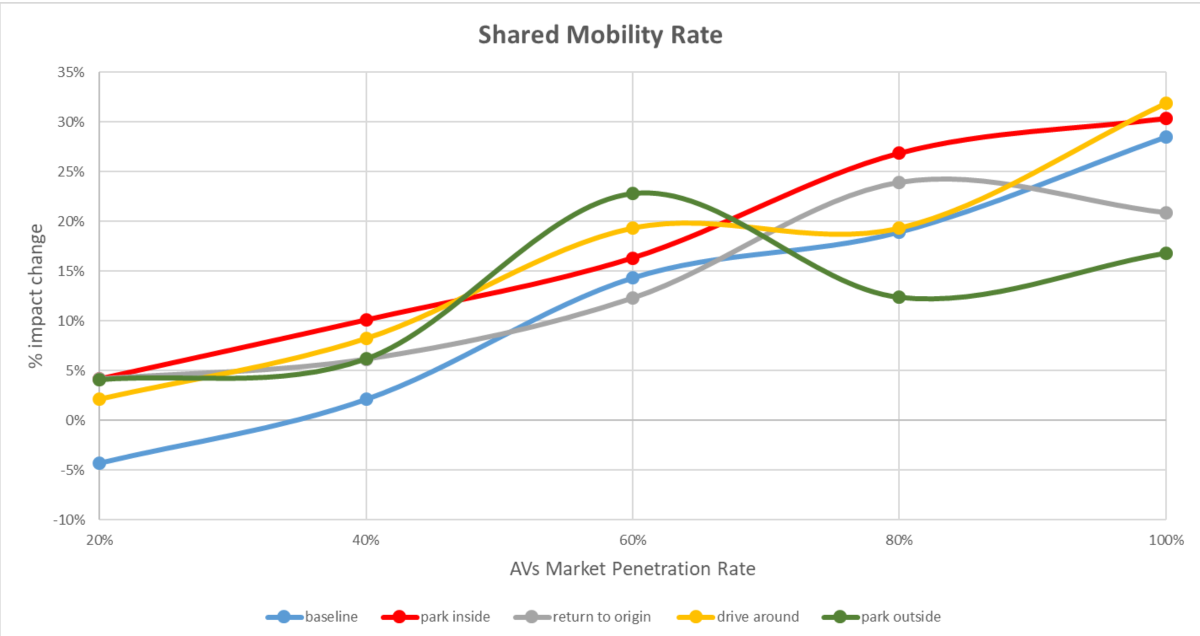
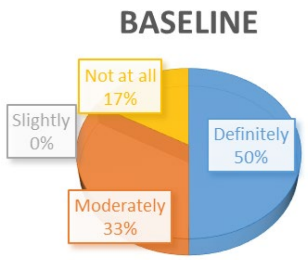


Figure 4.64 1st round Delphi shared mobility rate results for the CAV parking price policies scenarios

In the 2nd round questionnaires, the majority of the experts agreed definitely (50%) or moderately (33%) with the first-round curves (Figure 4.65). One expert (17%) suggested that all scenarios will increase by only 5% shared mobility rate.



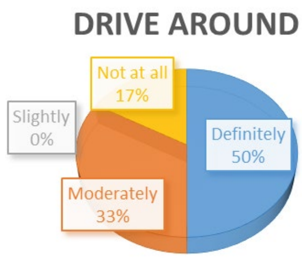


Figure 4.65: 2nd round Delphi shared mobility rate results for baseline and CAVs driving around

4.5.4 Parking space regulations

According to experts, shared mobility rates will be increased after the introduction of AVs in the baseline scenario, as well as after the implementation of the parking space interventions (Figure 4.66). More precisely, for 100% AVs market penetration rate shared mobility rate will increase by 11,4% for the baseline scenario. Replacing on-street parking spaces with space for public use, with driving lanes or with pick-up/drop-off parking spaces will increase the studied impact by 46,5%, 13,3% and 19,4% respectively for 100% AVs market penetration rate.

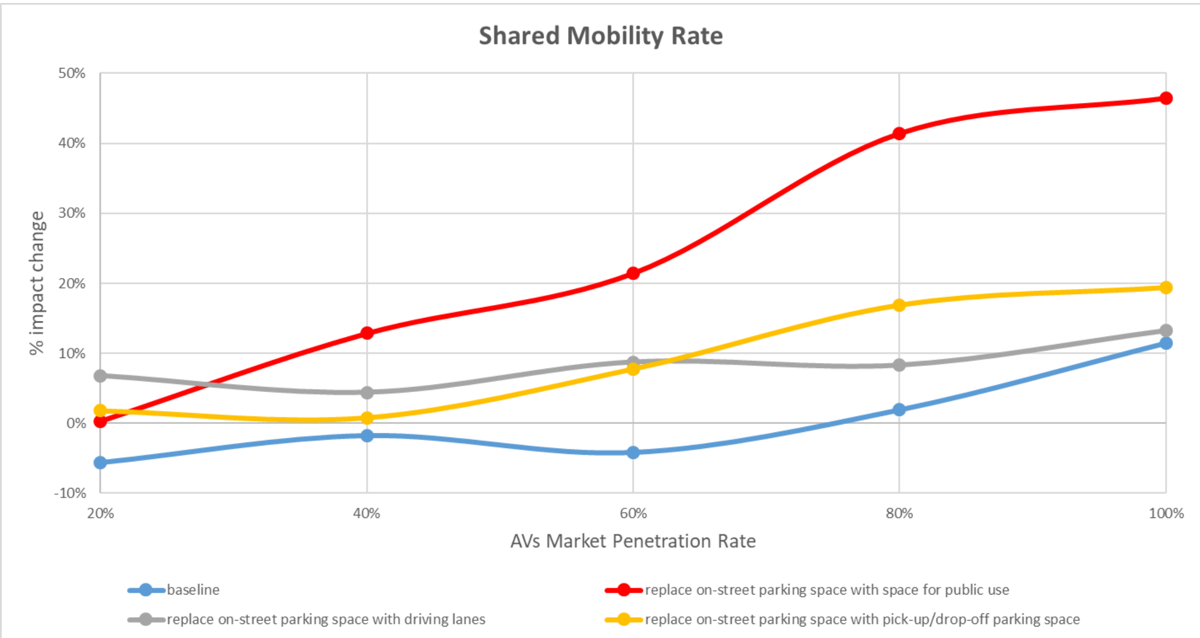


Figure 4.66: 1st round Delphi shared mobility rate results for parking space regulation scenarios

In the 2nd round questionnaires, all the experts agreed definitely with the first-round curves (Figure 4.67).

Figure 4.67: 2nd round Delphi shared mobility rate results for baseline and replacing on-street parking space with driving lanes

4.5.5 Automated ride sharing

According to experts, shared mobility rates will be increased after the introduction of AVs in the baseline scenario, as well as after the introduction of automated ridesharing (Figure 4.68). More precisely, for 100% AVs market penetration rate shared mobility rate will increase by 48% for both scenarios.

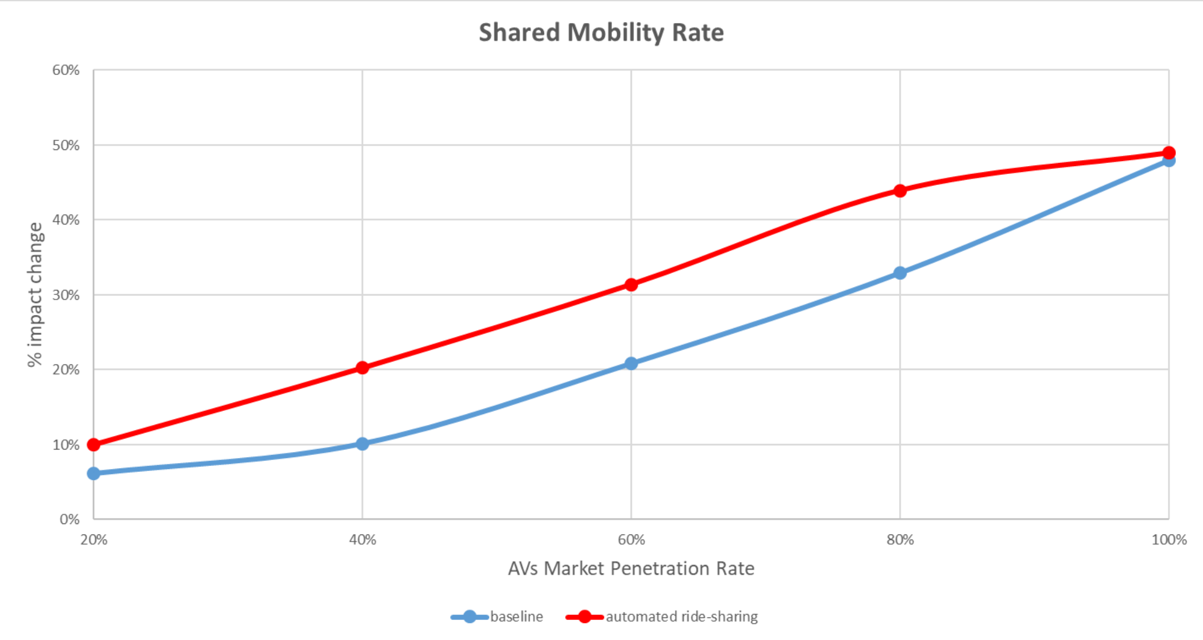


Figure 4.68: 1st round Delphi shared mobility rate results for the automated ridesharing scenarios

The majority of the 2nd round participants stated that they definitely (16%) or moderately (50%) agreed with the resulted 1st round trends for the baseline and the automated ridesharing scenarios (Figure 4.69). Some experts stated that they slight (13%) or not at all (17%) agreed the impact of these scenarios on modal split using active travel and stated that it is overestimated and that the baseline scenario will negatively affect modal split by 10%.

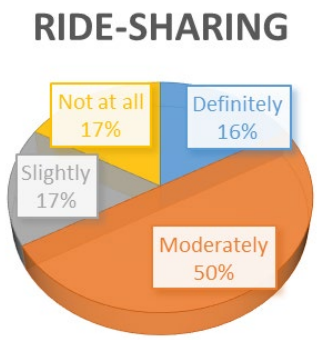


Figure 4.69: 2nd round Delphi shared mobility rate results automated ridesharing

4.5.6 Green Light Optimal Speed Advisory (GLOSA)

According to experts, shared mobility rates will be increased after the introduction of AVs in the baseline scenario (Figure 4.70). More precisely, for 100% AVs market penetration rate shared mobility rate will increase by almost 48%. Regarding the GLOSA scenario, experts suggest a general increase (6% to 14,6%) of shared mobility rate.

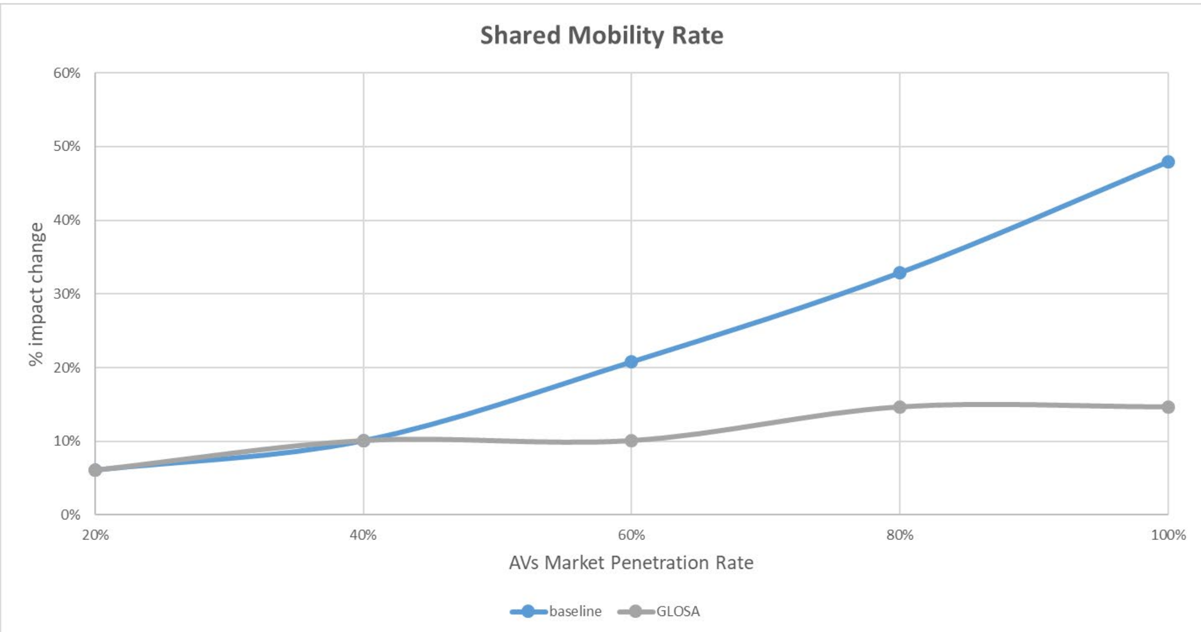


Figure 4.70 1st round Delphi shared mobility rate results for GLOSA scenarios

The majority of the 2nd round participants stated that they definitely (16%) or moderately (50%) agreed with the resulted 1st round trends for the baseline scenario (Figure 4.71). Some experts (34%) stated that the impact of this scenario on modal split using active travel is overestimated and that the baseline scenario will negatively affect modal split by 10%. According to 50% of experts, GLOSA will not at all affect the studied impact.

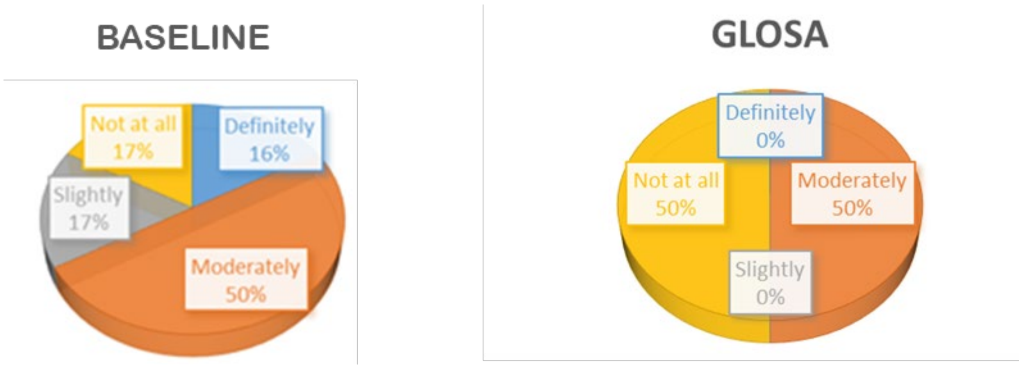


Figure 4.71: 2nd round Delphi shared mobility rate results for baseline and GLOSA scenarios

4.6 Vehicle utilisation rate

Vehicle utilisation rate is considered as the percentage of time a vehicle is in motion (not parked). The impact of the implementation of automation related interventions is calculated based on the experts' answers in the Delphi questionnaires.

4.6.1 Road use pricing

The general experts' opinion is that the introduction of automation in the urban environment will lead to an increase of vehicle utilisation rate, which is compatible with the resulted impact on the amount of travel and on modal split for the baseline scenario (Figure 4.72). More precisely, the baseline scenario (no intervention) will have the biggest impact on vehicle utilisation rate leading to an increase of 48% for AVs market penetration of 100%. Regarding the city toll scenarios, they present similar curves depending on the AVs market penetration rate and all increase vehicle utilisation rate by 14,4% for the empty km pricing, by 15,4% for the static city toll and by 18,4% for the dynamic city toll.

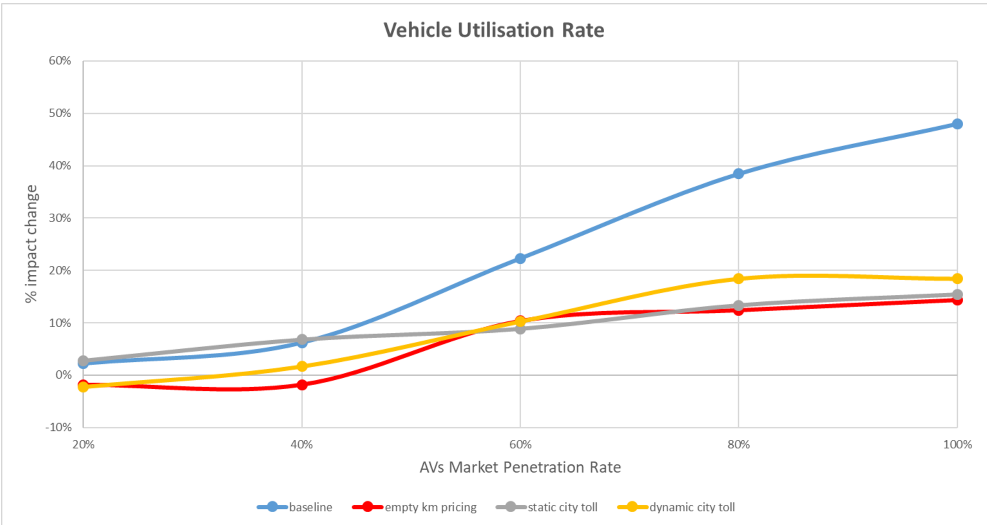


Figure 4.72: 1st round Delphi vehicle utilisation rate results for the city toll scenarios

The majority of the 2nd round participants stated that they agree definitely (14%) or moderately (72%) with the resulted trends for all scenarios (Figure 4.73). One expert (14%) slightly agreed with the curves and suggested that all scenarios will increase vehicle utilisation rate but less than presented in the first-round results, proposing an increase of 10% for the baseline scenario and 5% for all the city toll scenarios.

Figure 4.73: 2nd round Delphi vehicle utilisation rate results for empty km pricing and dynamic city toll

4.6.2 Provision of dedicated lanes on urban highways

The general experts’ opinion is that the introduction of automation in the urban environment will lead to an increase in vehicle utilisation rate, which is compatible with the resulted impact on the amount of travel and on modal split (Figure 4.74). More precisely, the baseline scenario (no intervention) will have the biggest impact on vehicle utilisation rate leading to an increase of 40,5% for AVs market penetration of 60%, and 32% for 100% AVs market penetration rate. Regarding the AV dedicated lane scenarios, they present different impacts depending on the AVs market penetration rate, but all increase vehicle utilisation rate. AV dedicated lane on the outermost motorway lane will increase vehicle utilisation rate by 26,9% in the long term. The introduction of an AV dedicated lane on the innermost motorway lane will increase the studied impact by 18,9% in the long term. Finally, the AV dedicated lane on the outermost motorway lane and A-road, as well as the dynamically controlled AV dedicated lane will both increase vehicle utilisation rate by 21,3%.

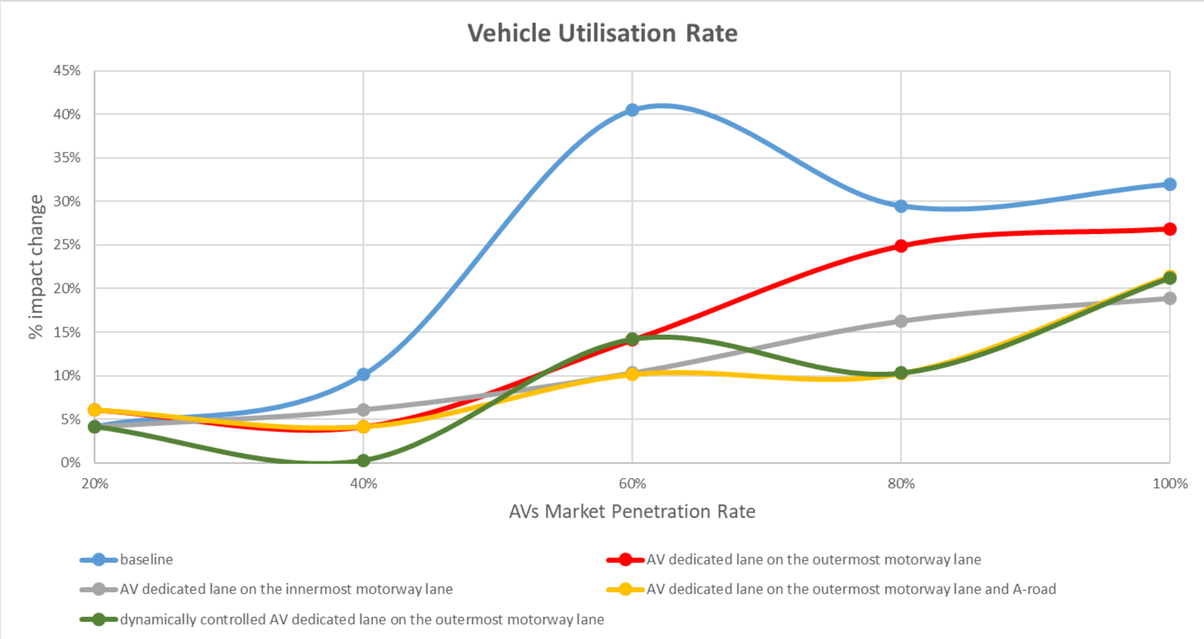


Figure 4.74: 1st round Delphi vehicle utilisation rate results for the AV dedicated lanes scenarios

All the 2nd round participants stated that they agree definitely (33%) or moderately (67%) with the resulted trends for AV dedicated lane on the outermost motorway lane, on the innermost motorway lane and on the outermost motorway lane and A-road scenarios (Figure 4.75). Two experts (33%) did not at all agree with the curves of the baseline and the dynamically controlled AV dedicated lane scenarios, suggesting that they should both linearly increase vehicle utilisation rate without any fluctuations depending on the AVs market penetration rate.

Figure 4.75: 2nd round Delphi vehicle utilisation rate results for baseline and AV dedicated lane on the outermost motorway lane.

4.6.3 Parking price policies

The general experts' opinion is that the introduction of automation in the urban environment will lead to an increase in vehicle utilisation rate, which is compatible with the resulted impact on the amount of travel and on modal split (Figure 4.76). More precisely, the baseline scenario (no intervention) will have the biggest impact on vehicle utilisation rate leading to an increase of 56,5% for AVs market penetration of 100%. Regarding the CAVs parking behaviours scenarios, they present different impacts depending on the AVs market penetration rate, but all increase vehicle utilisation rate. CAVs returning to origin will increase the vehicle utilisation rate by 42% in the long term. CAVs driving around will increase the studied impact by 40,3% in the long term. CAVs parking outside will increase vehicle utilisation rate by 35,4% in the long term. Finally, CAVs parking inside will affect the least the studied impact, leading to an increase of 19,2%

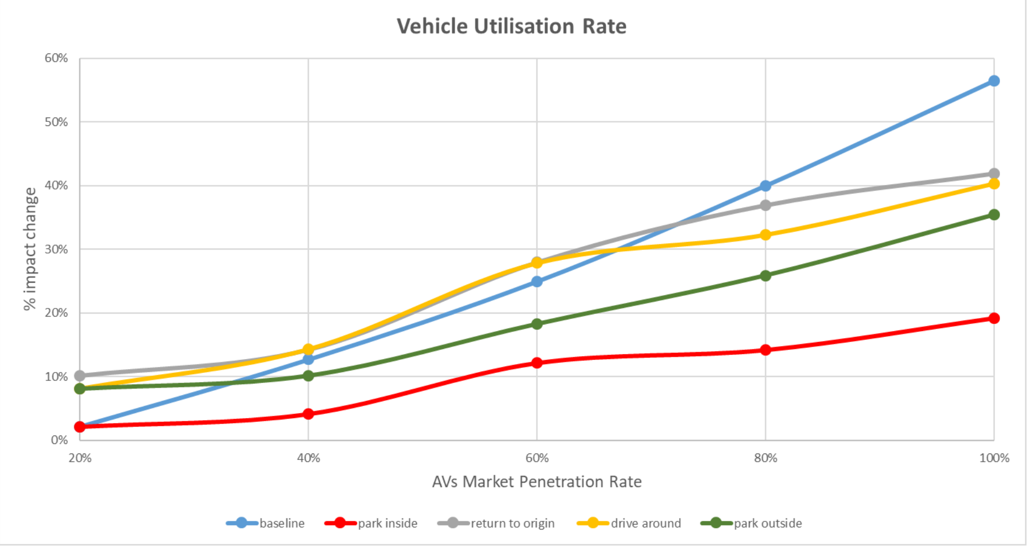
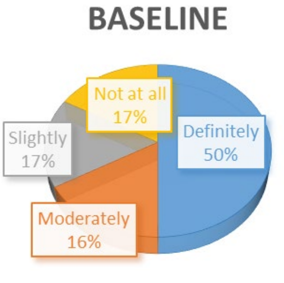


Figure 4.76: 1st round Delphi vehicle utilisation rate results for the CAV price policies behaviour scenarios

The majority of the 2nd round participants stated that they agreed definitely (50%) or moderately (16%-33%) with the resulted trends (Figure 4.77). One expert (17%) suggested that all the studied scenarios will lead to an increase of vehicle utilisation rate, but less that proposed in the 1st round, with an average of 5%.



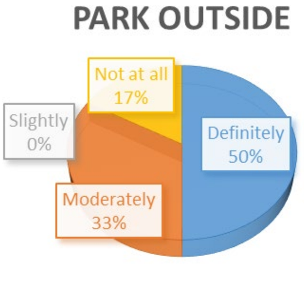


Figure 4.77: 2nd round Delphi vehicle utilisation rate results for baseline and CAVs parking outside

4.6.4 Parking space regulations

The general experts' opinion is that the introduction of automation in the urban environment will lead to an increase in vehicle utilisation rate, which is compatible with the resulted impact on the amount of travel and on modal split (Figure 4.78). More precisely, the baseline scenario (no intervention) will have the biggest impact on vehicle utilisation rate leading to an increase of 19,3% for AVs market penetration of 100%. Regarding the parking regulations scenarios, they present different impacts depending on the AVs market penetration rate. Replacing on-street parking space with space for public use will increase vehicle utilisation rate in the short-term vehicle utilisation rate reaching 6,7% for 40% AVs market penetration rate, then by increasing AVs market penetration rate, the studied impact will be reduced reaching -2% for 100% AVs MPR. On the other hand, replacing on-street parking spaces with pick-up/drop-off parking spaces will reduce vehicle utilisation rate by 7,3% in the short term but in the long term with 100% AVs MPR this intervention will not affect the studied impact. Finally, replacing on-street parking spaces with driving lanes will lead to a small increase of 2-5% of vehicle utilisation rate.

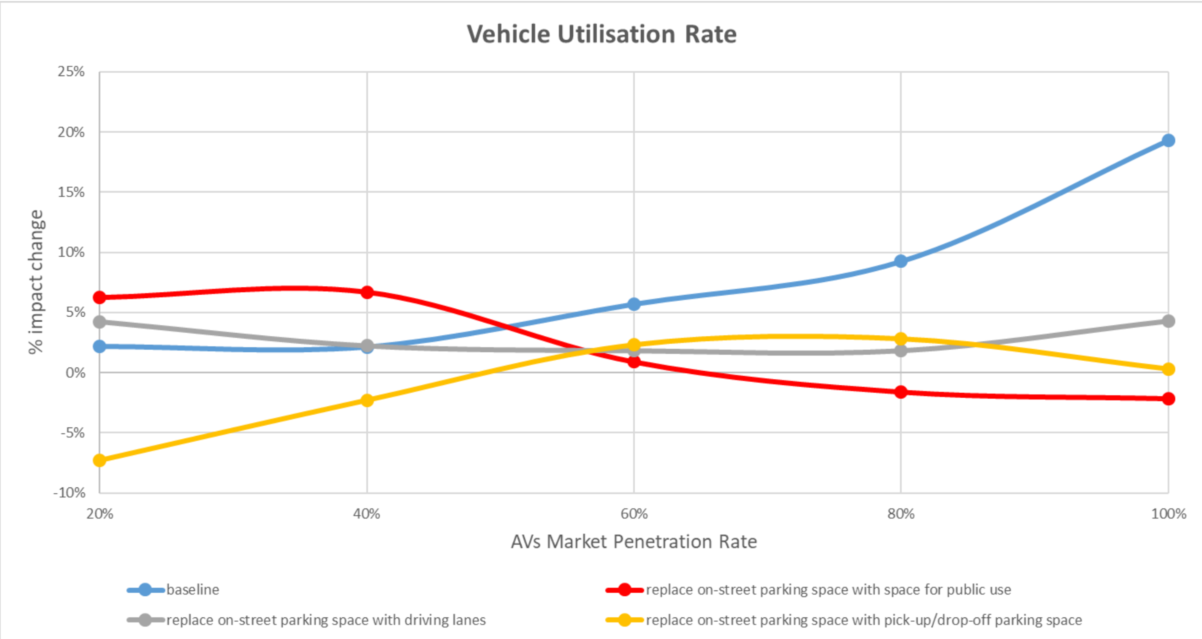


Figure 4.78: 1st round Delphi vehicle utilisation rate results for parking space regulation scenarios

All the 2nd round participants stated that they agreed definitely (20%-60%) or moderately (40%-80%) with the resulted trends (Figure 4.79). One expert suggested that all the studied scenarios will lead to an increase of vehicle utilisation rate. More precisely, the baseline scenario will increase the studied impact by 10% and all the parking regulations scenarios will lead to an average increase of 20%.

Figure 4.79: 2nd round Delphi vehicle utilisation rate results for baseline and replacing on-street parking space with driving lanes

4.6.5 Automated Ride Sharing

The general experts' opinion is that the introduction of automation in the urban environment will lead to an increase in vehicle utilisation rate, which is compatible with the resulted impacts on the amount of travel and on modal split for the baseline scenario (Figure 4.80). More precisely, the baseline scenario (no intervention) will have the biggest impact on vehicle utilisation rate leading to an increase of 50,4% for AVs market penetration of 100%. Regarding automated ridesharing, experts suggested a progressive increase on vehicle utilisation rate of about 20%.

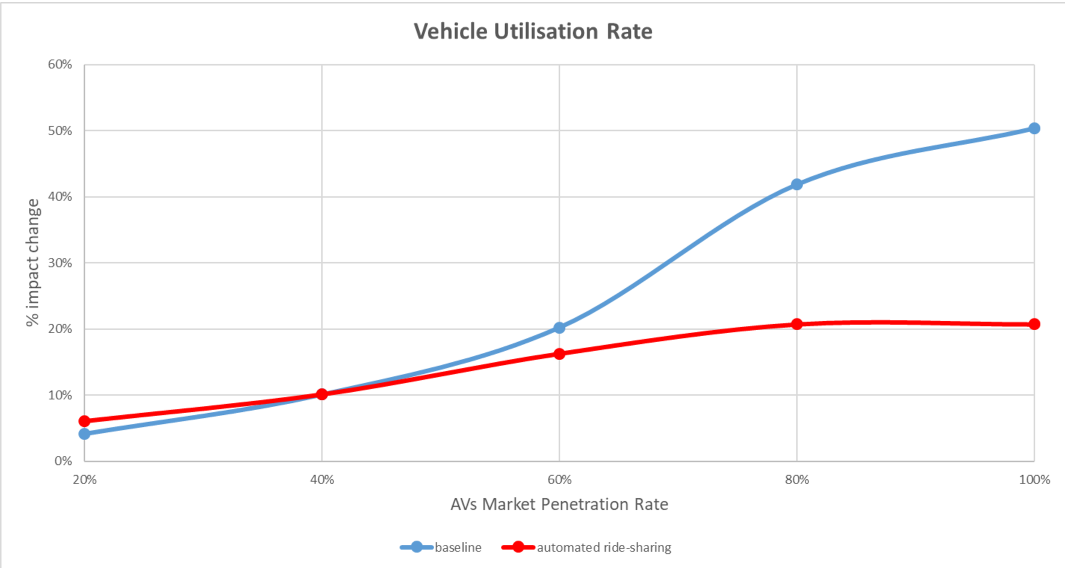


Figure 4.80: 1st round Delphi vehicle utilisation rate results for the automated ridesharing and GLOSA scenarios

The majority of the 2nd round participants stated that they moderately (67%) agreed with the resulted 1st round trends for the automated ridesharing scenario (Figure 4.81). Two experts (33%) stated that the impact of automated ridesharing on vehicle utilisation rate will be higher than in the 1st round, proposing an average increase of 25%. According to 50% of experts, the baseline scenario curve is overestimated for higher AVs market penetration rate, suggesting a maximal increase of 20% on vehicle utilisation in the long term.

Figure 4.81: 2nd round Delphi vehicle utilisation rate results for baseline automated ridesharing

4.6.6 Green Light Optimal Speed Advisory (GLOSA)

The general experts' opinion is that the introduction of automation in the urban environment will lead to an increase in vehicle utilisation rate, which is compatible with the resulted impacts on the amount of travel and on modal split for the baseline scenario (Figure 4.82). More precisely, the baseline scenario (no intervention) will have the biggest impact on vehicle utilisation rate leading to an increase of 50,4% for AVs market penetration of 100%. GLOSA will increase the studied impact by 6% to 10%.

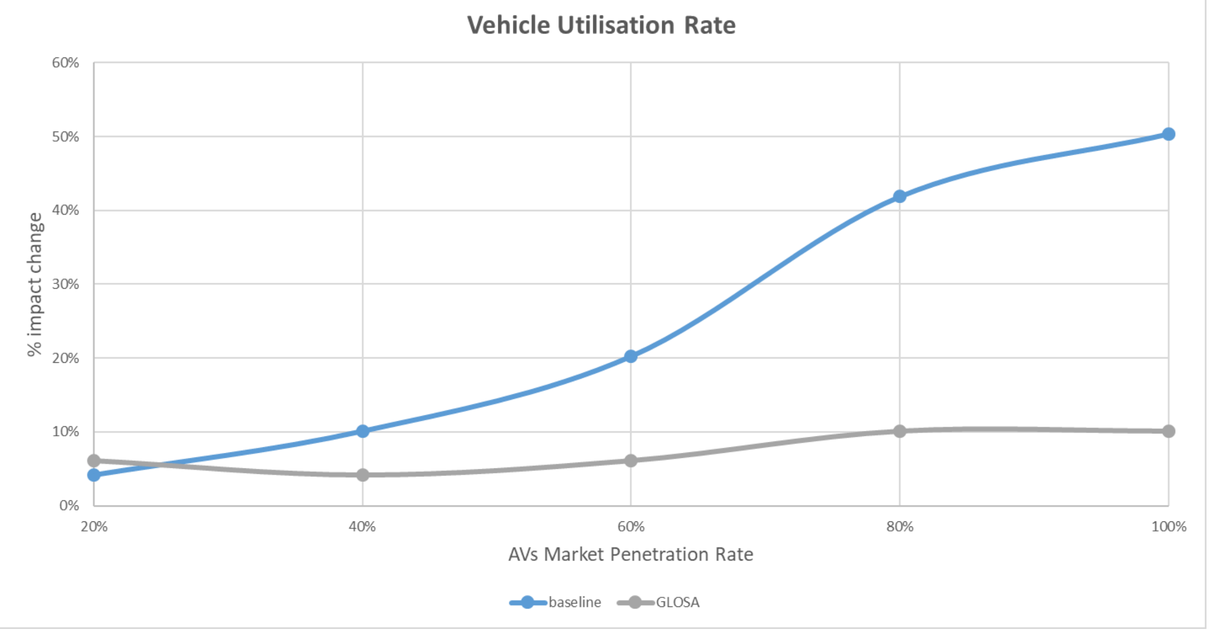


Figure 4.82 1st round Delphi vehicle utilisation rate results for the automated ridesharing and GLOSA scenarios

According to 50% of experts GLOSA will not at all affect the studied impact and the baseline scenario curve is overestimated for higher AVs market penetration rate, suggesting a maximal increase of 20% on vehicle utilisation rate in the long term (Figure 4.83).

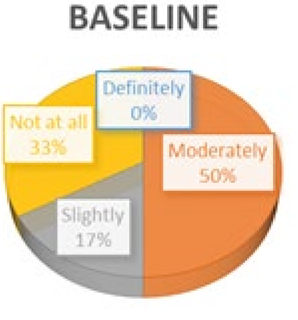


Figure 4.83 2nd round Delphi vehicle utilisation rate results baseline scenario

4.7 Vehicle occupancy

The Delphi method was used to estimate the impact of automation on vehicle occupancy (average percentage of seats in use).

4.7.1 Road use pricing

According to experts, city toll scenarios will progressively increase vehicle occupancy. Empty km pricing and static city toll will have the same impact on vehicle occupancy for 100% AVs market penetration rate reaching an increase of 18,2% (Figure 4.84). The introduction of a dynamic city toll will increase the most vehicle occupancy reaching 26,9%. On the other hand, the introduction of AVs (baseline scenario) will not significantly affect vehicle occupancy, leading to a reduction of 5,6% for lower AVs market penetration rate, and reaching an increase of 6,8% in the long term.

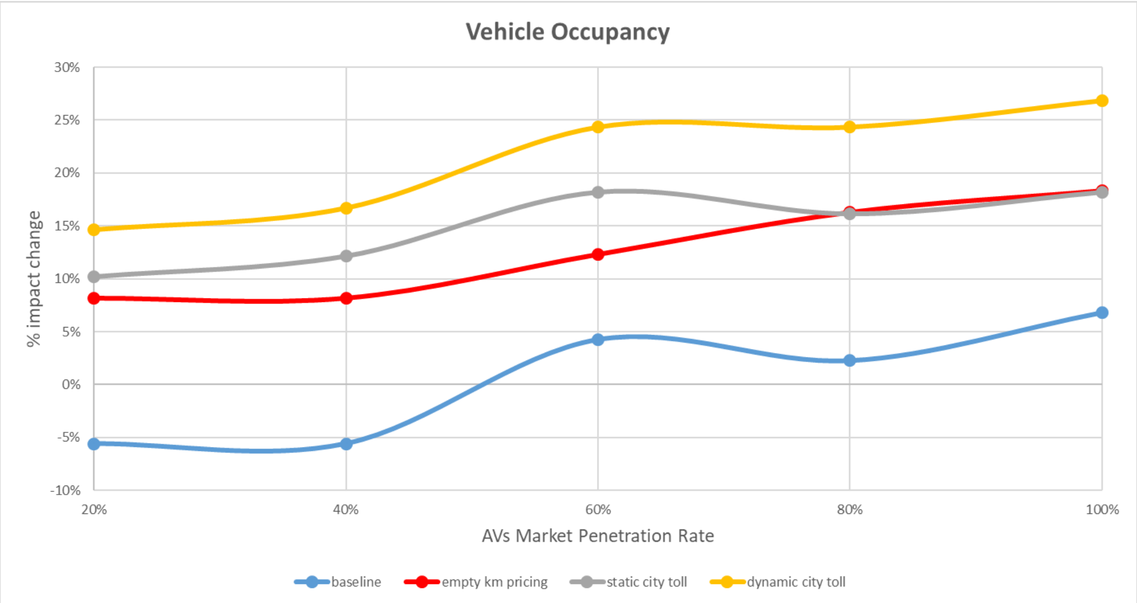


Figure 4.84 1st round Delphi vehicle occupancy results for the city toll scenarios

In the 2nd Delphi round questionnaires, the majority of experts definitely (14%) or moderately (43%-72%) agreed with the resulted curves (Figure 4.85). The experts (14%-43%) that slightly agreed with the 1st round results suggested that all studied scenarios will increase by 10% vehicle occupancy.

Figure 4.85: 2nd round Delphi vehicle occupancy results for static city toll and empty km pricing

4.7.2 Provision of dedicated lanes on urban highways

According to experts, AV dedicated lane scenarios will increase progressively vehicle occupancy (Figure 4.86). The AV dedicated lane on the outermost motorway lane and the dynamically controlled AV dedicated lane scenarios, present similar fluctuations with the increase of AVs market penetration rate, reaching an impact of 16,9% and 19,3% respectively. The AV dedicated lane on the outermost motorway lane and A-road will increase the least vehicle occupancy reaching 10,3%. On the other hand, the introduction of AVs (baseline scenario) will not significantly affect vehicle occupancy, leading to a maximum reduction of 4% for 60% AVs market penetration rate.

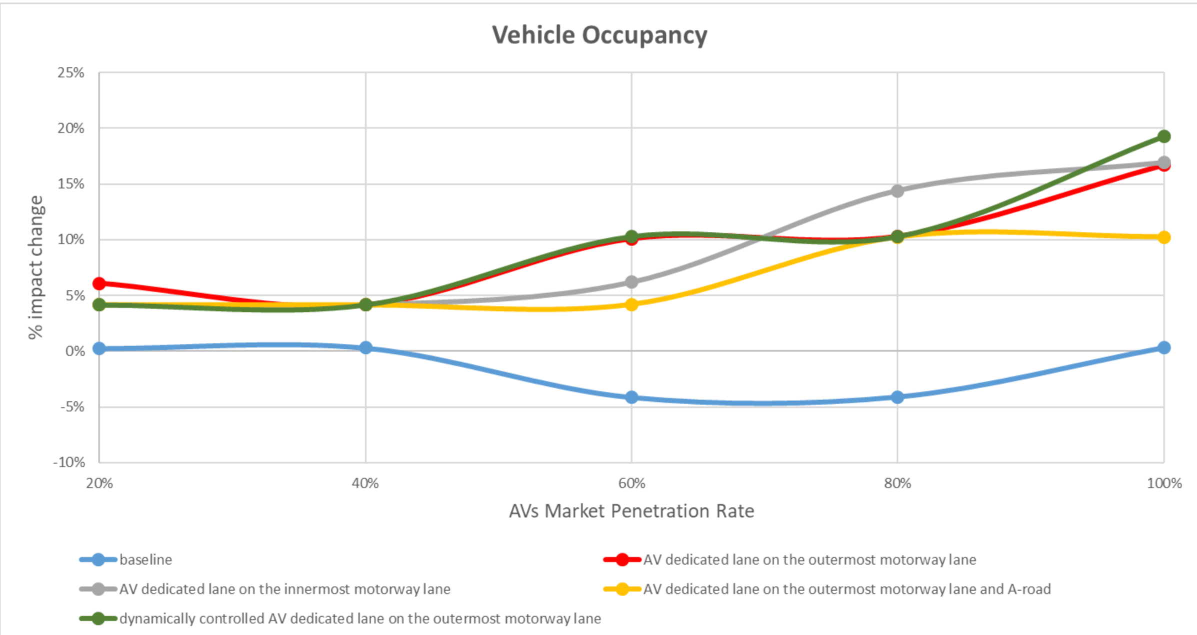


Figure 4.86 1st round Delphi vehicle occupancy results for the AV dedicated lanes scenarios

In the 2nd Delphi round questionnaires, all experts stated that they moderately agreed with the resulting curves for the AV dedicated lane on the outermost and in the innermost motorway lane (Figure 4.87). On the other hand, the majority of experts moderately (67%) agreed with the other scenarios. Two experts (33%) do not at all agree with the proposed curves and suggested that the baseline scenario will reduce by -8% vehicle occupancy for 100% AVs market penetration rate, and that the AV dedicated lane on the outermost motorway lane and A-road as well as the dynamically controlled AV dedicated lane should have similar curves to the other AV dedicated lane scenarios.

Figure 4.87: 2nd round Delphi vehicle occupancy results for baseline and AV dedicated lane on the innermost motorway lane

4.7.3 Parking price policies

According to experts, CAVs parking inside will increase progressively vehicle occupancy reaching 25,6% (Figure 4.88). CAVs driving around will slightly reduce vehicle occupancy in the short term but when AVs market penetration rate reached 100%, the impact presents an increase always less than 5%. The introduction of CAVs returning to origin and parking outside behaviour will increase vehicle occupancy in the long term by 10,4% and 19,3% respectively. On the other hand, the introduction of AVs (baseline scenario) will reduce vehicle occupancy by 5,6%.

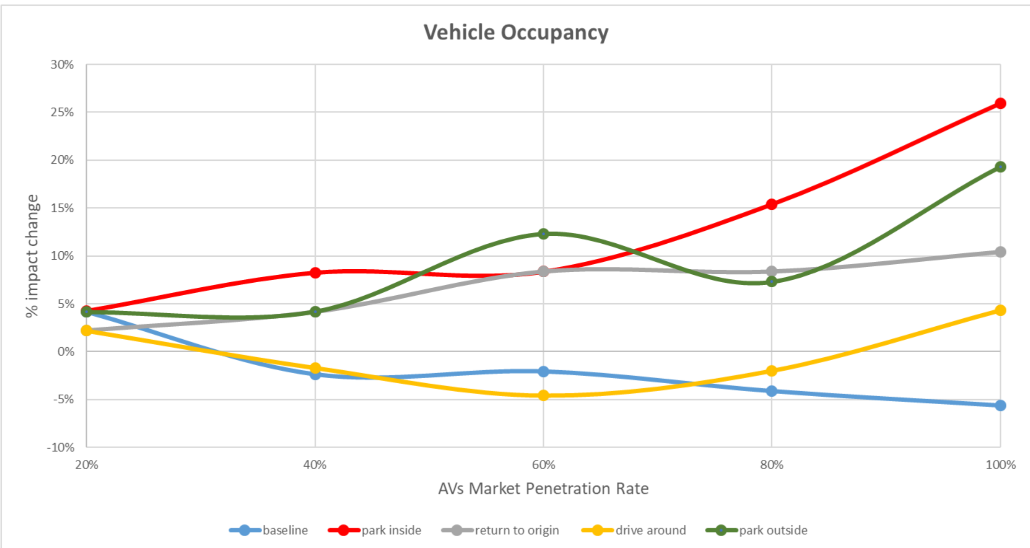


Figure 4.88 1st round Delphi vehicle occupancy results for CAV parking price policies scenarios

In the 2nd Delphi round questionnaires, experts stated that they agreed definitely (50%) or moderately (16%) with the resulted curves (Figure 4.89). Two experts (33%) suggested that none of the scenarios will affect the studied impact, especially the CAV parking behaviour scenarios that should have more empty kilometres, so less occupancy.

Figure 4.89: 2nd round Delphi vehicle occupancy results for baseline and CAVs parking inside

4.7.4 Parking space regulations

According to experts, replacing on-street parking space with space for public use or with pick-up/drop-off parking spaces will increase progressively vehicle occupancy, reaching 18,9% and 14,4% respectively for 100% AVs market penetration rate (Figure 4.90). On the other hand, the introduction of AVs (baseline scenario) and replacing on-street parking spaces with driving lanes will reduce vehicle occupancy by 9,2% and 9,7% respectively.

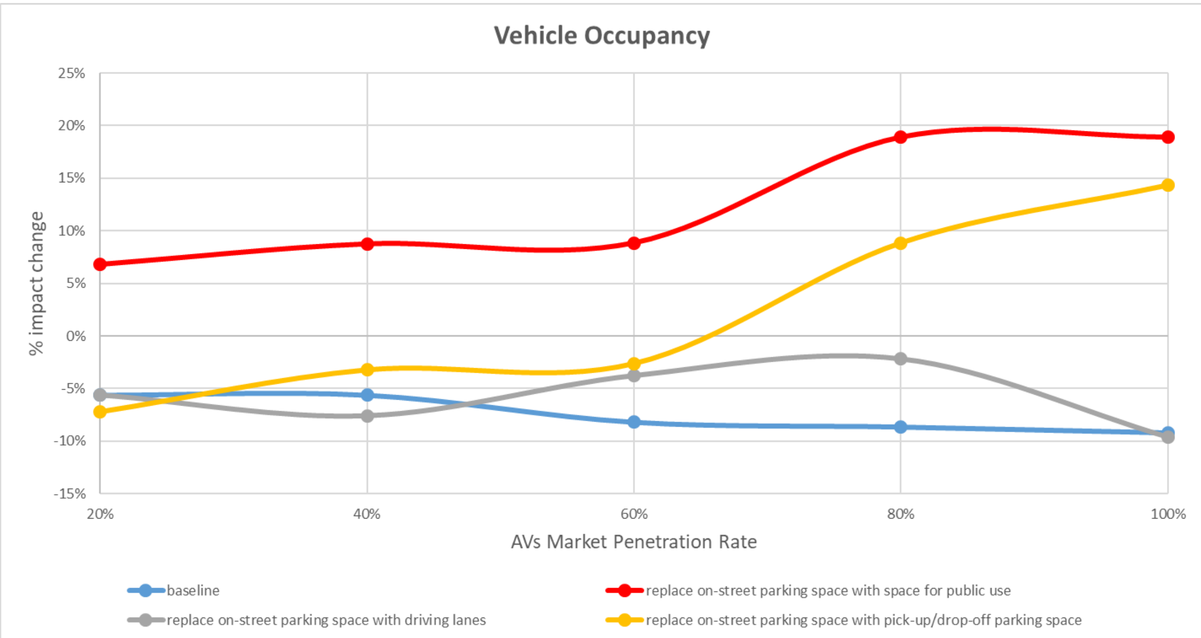


Figure 4.90: 1st round Delphi vehicle occupancy results for parking space regulation scenarios

In the 2nd Delphi round questionnaires, all experts stated that they agreed definitely (40%-100%) or moderately (0%-60%) with the resulted curves (Figure 4.91).

Figure 4.91: 2nd round Delphi vehicle occupancy results for baseline and replacing on-street parking space with space for public use

4.7.5 Automated ride sharing

According to experts, the introduction of AVs in the urban environment as well as the automated ridesharing will increase vehicle occupancy in the long term (Figure 4.92). The automated ridesharing service presents the biggest impact on vehicle occupancy, reaching an increase of 21%. Baseline scenario does not affect vehicles occupancy in the short term but the impact increases for higher AVs market penetration rates, reaching 10,7%.

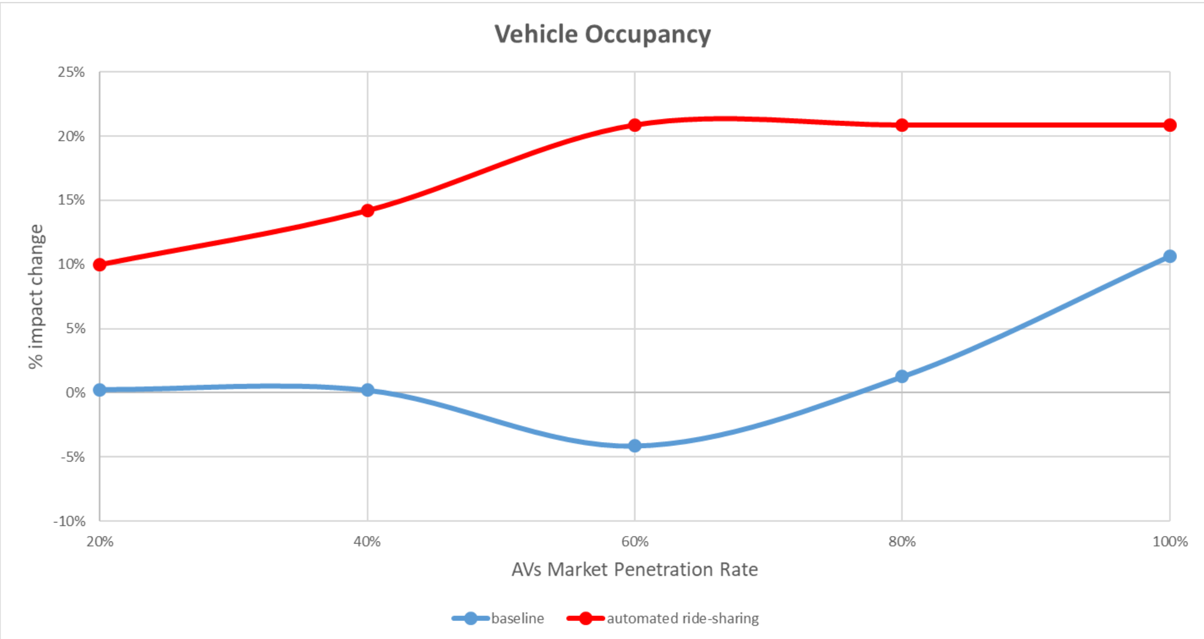


Figure 4.92: 1st round Delphi vehicle occupancy results for the automated ridesharing and GLOSA scenarios

In the 2nd Delphi round questionnaires, the majority of experts definitely (16%) or moderately (67%) agreed with the resulted curves for the baseline and automated ridesharing scenarios (Figure 4.93).

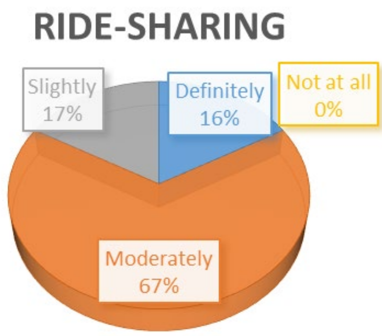


Figure 4.93: 2nd round Delphi results automated ridesharing

4.7.6 Green Light Optimal Speed Advisory (GLOSA)

According to experts, the introduction of AVs in the urban environment will increase vehicle occupancy in the long term (Figure 4.94). The Baseline scenario does not affect vehicles occupancy in the short term but the impact increases for higher AVs market penetration rates, reaching 10,7%. Regarding the GLOSA scenario, experts suggest a general increase (6,1%) of vehicle occupancy regardless of the AVs market penetration rate.

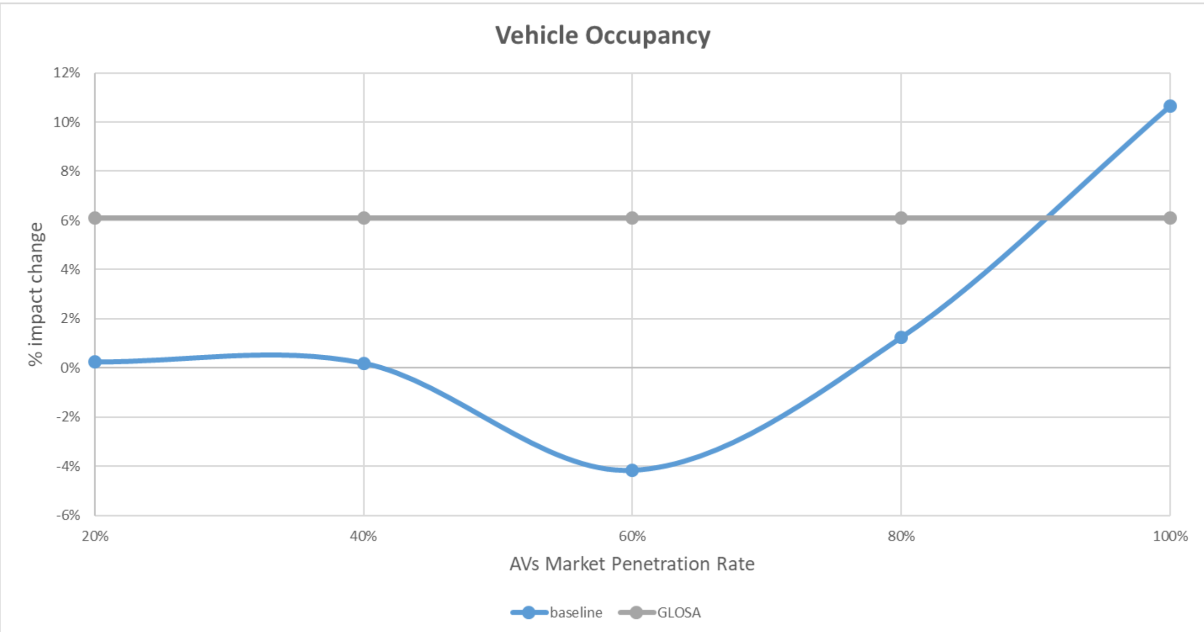


Figure 4.94: 1st round Delphi vehicle occupancy results for GLOSA scenarios

In the 2nd Delphi round questionnaires, the majority of experts definitely (16%) or moderately (67%) agreed with the resulted curves for the baseline scenario (Figure 4.95). The majority of experts also stated they slightly (67%) or not at all (17%) agreed with the 1st round results of the GLOSA scenario and suggested that this intervention will not affect the studied impact.

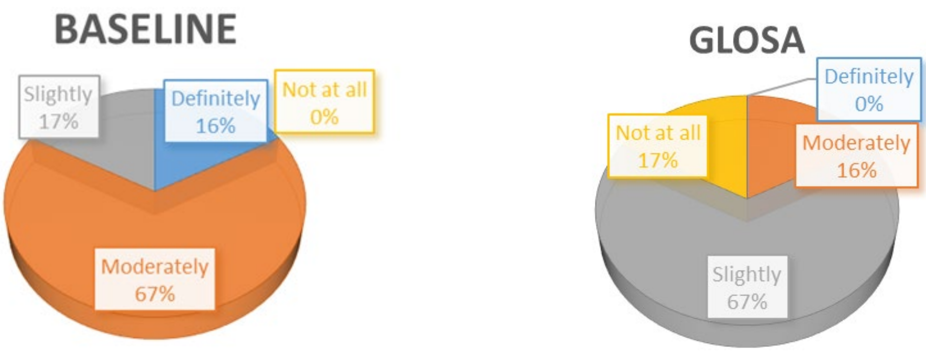


Figure 4.95: 2nd round Delphi vehicle occupancy results for baseline scenario and GLOSA

5 Discussion

The key policy interventions (sub-use cases), identified through literature review and discussions with stakeholders' reference group, were tested for passenger transport to analyse some of the medium-term or system level impacts of CCAM, including the amount of travel, congestion, modal split using public transport, modal split using active travel, shared mobility rate, vehicle utilization rate and vehicle occupancy. Since no real-world data is available, CAVs behaviours were modelled according to the available knowledge found through existing literature and experimental studies' findings on early level automated vehicular systems. Various methods were used on the basis of their applicability for the assessment of the studied impacts, including microscopic simulation, mesoscopic simulation, system dynamics modelling, and Delphi study. The term baseline (no policy intervention) corresponds to increasing automation only without implementation of any other policy measure. Under the micro-simulation analysis different networks were used based on the requirements of the SUC. It should be noted that baseline trend was found to have some commonalities between different networks, however, the specific trend varied based on the network characteristics. The trends from Delphi study are based on the expert’s interpretation of the questions as well as assumptions and perceptions of the future outcomes. The analysis performed under different methods provided several insightful findings on the medium-term impacts, which are discussed, as follows:

Congestion

The impact on congestion was analysed through network-level traffic delays. For the baseline or no policy intervention scenario, which included MPR of CAVs only without any other policy intervention, the microsimulation results from different study networks generally showed some oscillations (increase and decrease) in delays, especially under mixed fleet scenarios involving HDVs and CAVs. The increase in delays only occurred under mixed fleet scenarios. However, the specific trend varied under the different study networks.

The microsimulation results for the provision of CAV dedicated lanes in the Manchester network indicated a better performance under the ‘A-road innermost lane’ configuration, considering only one dedicated lane. Results showed lesser delays under this case as compared to the other placement strategies (A-road outermost lane, A-road and motorway innermost lane, motorway only with innermost lane) and baseline scenario (without CAV dedicated lane). Since only one lane was considered, delays increased at higher MPR (20-40-40). The most optimal performance was observed at a moderate MPR scenario (60-40-0).

Under parking price policies, it was found that, overall, delay decreases with the increasing MPR in the baseline scenario. However, this impact could diminish with various parking prices strategies tested in this deliverable. The main reason is that most vehicles either drive around or return to origin under the tested policies, leading to higher traffic within the network, causing congestion on the roads. The delay increases up to 39% with the ‘drive around’ scenario of parking behaviour. The increase was reached 33% for the 'balanced scenario and 40% for the 'Heavy Return to Origin and Park Outside' scenario.

Parking space regulations results from microsimulation showed that replacing on-street parking with driving lane, cycle lane and public spaces can potentially lead to better traffic performance (40 to 51% reduction in delays w.r.t baseline) as compared to the other tested measures, including removing half of the parking spaces and replacing on-street parking with pick-up/drop-off spaces. The negative impact of replacement with pick-up/drop-off spaces is due to increased stop-and-go events while vehicles pick up and drop off passengers, and leading to more interruptions in the flow, and increased delays. The results also revealed that replacing half of the on-street parking spaces may not provide the expected improvement in reducing delays in the city centre, especially with congested conditions.

Microsimulation results on introducing an automated ridesharing service showed an increase in delay time for all market penetration rates compared to the baseline scenario (increasing MPR of CAVs only without any policy intervention) regardless of the served demand. The increase was found to be strongly related to the travellers' willingness to share, where lower values are noticed with higher willingness to share and vice-versa. One of the potential reasons for increased delays is the increased number of trips and the empty VKT caused by repositioning trips to reach new travellers.

The delays were found to reduce with the application of the GLOSA system with fixed-time signal controllers. The implementation of the GLOSA system on multiple intersections showed further improvement in reducing delays as compared to GLOSA system implementation on a single intersection along the study corridor.

Amount of travel

The impact on the amount of travel was analysed through total distance travelled, and the results were obtained from mesoscopic and microscopic simulation methods as well as the Delphi study.

Mesoscopic simulation results showed that the measures implemented as static road use pricing show more consistent model behaviour with respect to the average travel distance. In contrast, the dynamic road use pricing implementation allows room for effects in traffic flow and mode choice interactions that exhibit higher complexity and thus are harder to predict. An increased share of automated vehicles shows a minor tendency to decrease daily average travel distances, while high RUP pricing shows a reduction of those distances more clearly. A more detailed analysis in the case studies will allow further conclusions.

The baseline (no policy intervention) results from microsimulation showed an irregular trend in the distance travelled with increasing MPR of CAVs, where the trend varied between different study networks used in the project. Microsimulation results of dedicated lanes SUC tested in the Manchester network showed increased distance travelled under A-road innermost lane configuration for CAV dedicated lane compared to other placement strategies and baseline scenario (increasing MPR of CAVs with no CAV dedicated lane). From the Delphi study, experts predicted an increase in the amount of travel under AV dedicated lanes in the long term. General experts' opinion indicated that AV dedicated lane on the outermost motorway lane and the dynamically controlled AV dedicated lane will mostly affect the amount of travel.

The implementation of parking price policies was found to negatively affect the amount of travel as compared to the baseline scenario. The maximum impact was found under the case of ' drive around' strategy. The investigation on the microsimulation results revealed that with different parking behaviours tested under this SUC, the network flow is negatively affected, leading to congestion and, consequently, lesser distance travelled than that under the baseline condition. It was found that the 'drive around' can decrease the total distance travelled by up to 70%. Whereas 'balanced' and 'heavy return to origin and park outside' can reduce it by up to 26% and 21%, respectively. The findings suggest that 'drive around' and 'balanced' can negatively impact the total distance travelled. In this regard, the Delphi experts also estimated a reduction in the amount of travel compared to the baseline. However, the responses suggested that the 'park outside' and 'drive around' strategies can have a potentially positive impact on the amount of travel compared to the 'park inside' and 'return to origin' scenarios.

Various parking space regulations were tested on a microsimulation model of Leicester city. The results from the microsimulations showed an increase in travelled distance when on-street parking spaces were replaced with driving lanes, cycle lanes, and public spaces compared to the baseline scenario as well as the other tested strategies, including 'removing 50% of the parking spaces' and 'replacing pick-up/drop-off' spaces. The main reason behind this is the improved network flow under those parking space regulation schemes where travel distance was found to be increased, allowing more vehicles in the network during the simulation period and consequently increasing distance travelled. The results from the Delphi study indicated that in the baseline scenario or with the introduction of CAVs only in an urban environment will, in general, increase the amount of travel. The experts estimated that replacing on-street parking with driving lanes will lead to an increase in the amount of travel in the short-term (at low MPRs) and then decrease with regards to baseline in the long-term (at higher MPRs). However, the experts also indicated that 'replacing on-street parking with driving lanes' will increase the amount of travel the most as compared to 'replacement with pick-up/drop-off spaces, and replacement with public spaces' reaching almost 18% for AVs market penetration rate of 100%, which is in-line with the microsimulation analysis findings on this SUC. The experts also indicated that replacing on-street parking spaces with public use or with pick-up/drop-off parking spaces will not affect the amount of travel in the long term.

Microsimulation results suggest that deploying an automated ride-sharing service in an urban area will worsen traffic conditions due to the increased number of trips and the empty VKT caused by making repositioning trips to reach new travellers. The circulating behaviour of shared vehicles (SAV) is also a potential reason for causing congestion since SAVs tend to use optimal routes to serve their customers. These routes could be low-capacity roads that are not prepared to handle high traffic volumes (Overtoom et al., 2020). The results also suggest that this negative impact could be reduced if more travellers are willing to use the introduced service as a ride-sharing service instead of an individual-trip service (taxi or free-floating car-sharing service). From Delphi results, experts' opinions indicated that the introduction of automated ridesharing services in the urban environment would progressively increase the amount of travel in the long term.

Microsimulation results showed an increase in total distance travelled with the implementation of the GLOSA system on the test network as compared to the baseline (without GLOSA) scenario. Implementation on more intersections along the test corridor was found to result in increased distance travelled as compared to implementation on single or two junctions, indicating improvement in traffic flow, reduction in travel time, or overall improvement in traffic performance. From Delphi results, there was a mixed opinion on the impact of GLOSA on the amount of travel. The first round, results indicated a slight increase with increasing MPR of AVs in the short term; however, in the second round, almost 50% of the participants predicted no effect on the amount of travel.

Modal split using public transport

The mesoscopic simulation results for almost all assumed scenarios show a consistent decrease in public transport mode split (- 2.5 %) when vehicle automation becomes more widely available. Due to high comfort and very direct access of passenger cars to most places within contemporary cities, automated vehicles absorb part of the public mode share. A maximum increase of 12 % can be discerned in the case of the introduction of prohibitive tolling levels, where the shift from cars towards public transport is the viable alternative that provides locomotion that bridges comparably large distances. According to Delphi results, the introduction of static city toll and dynamic city toll will both lead to an increase in modal split using public transport.

Overall, majority of experts in the Delphi study indicated that the introduction of AVs in urban environment will reduce the modal split of public transport, particularly in the long term (with higher MPR of AVs).

With regard to the provision of AV dedicated lanes on urban highways, the experts indicated that all the AV dedicated lanes scenarios either on the outermost or innermost motorway lane 'dynamically controlled on the outermost motorway lane' as well as under ‘outermost motorway lane and A-road' scenario, will negatively affect modal split using public transport with increasing MPR of AVs.

Under parking price policies, the majority of the experts’ opinions showed that AVs parking outside is the single intervention leading to an increased public transport model split with regards to baseline. This scenario was also indicated to, on average, positively impact the modal split of public transport with increasing MPR of AVs. All other parking policies, including 'park inside', 'driver around', and 'return to origin', were estimated to, on average, negatively impact model split using public transport.

With respect to baseline scenario, experts predicted an increase in modal split using public transport if on-street parking is replaced with public spaces, driving lanes, or pick-up/drop-off parking spaces.

The introduction of automated ridesharing will increase modal split using public transport as compared to the baseline scenario; however, the modal split of public transport is predicted to be negatively impacted due to automated ride sharing services with higher AVs market penetration rates.

The experts indicated that GLOSA will only negatively affect modal split using public transport near or at full AVs MPR, estimating a 10% reduction at 100% fleet penetration.

SD model results predicted that the percentage of public transport usage would slowly decrease with increasing MPR of AVs (baseline scenario) with a maximum decrease (almost 10%) at full fleet penetration. The SD results also indicated an increase in the public transport modal share due to the implementation of road use pricing compared to the baseline. With a 'balanced' parking policy, the SD model estimated a slight reduction in public transport modal split with increasing MPR and a slight increase at full MPR scenario, which was attributed to the increased congestion at 100% MPR of AVs with such parking policy.

The SD model results showed a strong impact on changes in public transport modal share due to replacing on-street parking with driving lanes. This is because having added capacity on roads would encourage more vehicles on roads potentially reducing the share of public transport users, particularly with increasing AVs MPR. The other regulation of removing 50% of on-street parking was found to have a marginal impact on modal shift to public transport.

The model results showed increased modal share in public transport due to automated ride sharing services, primarily due to the fact that this new mode was included as a public transport mode. However, this can likely decrease at very high or full MPR of AVs due to a potential increase in car ownership and use of private AVs.

Modal split of active travel

The mode split of active travel results from mesoscopic simulation showed only a minor decline is to be expected for increased automation (baseline). Here, a maximum increase of 4 % is possible in the case of prohibitive tolling. The applied definition of the impact of active travel does not allow for a more detailed analysis, which will be given in the case studies. It is clear, however, that active modes are mostly used for shorter trips, while the modal trip classification is made due to the mode covering the longest part of a trip. Any changes, for example, in extended access and egress walking stages will rarely be reflected by the trip-wise modal split. In this regard, the Delphi results predicted that the introduction of 'static city toll' and 'empty km pricing' would lead to an increase in modal split using active travel with respect to baseline scenario. On the other hand, dynamic city toll scenario would reduce modal split using active travel in the short term (lower MPRs of AVs); however, will considerably increase in the long term (at higher MPRs of AVs).

The SD model results also indicated a decrease in active travel with increasing MPR of AVs in the transport system (baseline scenario). The results predicted a significant increase in active travel due to road use pricing and balanced parking behaviours, as compared to that under the baseline scenario. This trend can be expected as such policies involving some sort of price would likely impact motorized travel and influence people to prefer the use of active modes. With parking space regulations, the SD model results indicated a slight increase in active travel due to replacing on-street parking with driving lanes. However, removing half of the parking spaces was found to increase active travel up to 70% MPR and become insensitive with a further increase in the fleet penetration. Automated ride sharing services due to serving passengers closest to their origins and destinations are expected to negatively impact active travel.

Overall, the Delphi study experts also predicted a decrease in active travel due to increasing automation (baseline). One of the potential reasons could be due to a general perception that AVs will increase door-to-door travel.

Under the AV dedicated lane scenarios, most of the experts indicated higher active travel as compared to the baseline scenario; however, with all dedicated lanes scenarios, on average, a decrease in active travel was indicated at higher MPRs of AVs.

The majority of the responses from experts indicated an increase in active travel due to different parking price policies as compared to the baseline scenario. The results further indicated that active travel would reduce the most under 'driver around' strategy with increasing automation by almost 22% in the long term (100% MPR). On the other hand, ‘parking inside' and 'returning to origin' parking strategies were predicted to reduce active travel in the long term by almost 15% and 12%, respectively.

Implementation of parking space regulations was indicated by the experts to have a positive impact on active travel, since finding a parking spot will be more difficult when reducing on-street parking space.

The first round of Delphi results indicated an increase in active travel than baseline scenario up to moderate MPR (around 60%), which will reduce at higher MPRs. Almost 50% of experts in the second round did not show agreement with this trend and indicated a decrease in active travel (up to 10%) under both baseline (automation) and the inclusion of automated ride sharing services.

The experts in the 1st round of Delphi indicated that GLOSA would cause a slight decrease in active travel almost up to 6% regardless of AV MPR. However, almost 50% of the experts in the 2nd round showed disagreement and indicated no effect on active travel due to GLOSA.

Shared mobility rate

The impact on shared mobility rate was analysed through the Delphi study. The majority of experts predicted an increase in shared mobility rate with the introduction of AVs only (baseline scenario).

The experts were of the view that city tolls will increase shared mobility rate as compared to the baseline scenario in the short term; however, they will reduce it at full fleet penetration (100% AVs MPR). Among all the city toll scenarios, the majority of the experts identified dynamic city toll to have the maximum impact on shared mobility rate.

According to the experts, under AVs dedicated lane scenarios, the shared mobility rate will reduce compared to the baseline scenario. On the other hand, under all dedicated lane scenarios, the shared mobility rate was indicated to have an irregular trend with increasing automation; however, it showed an increase in the long term. In this regard, the introduction of a dynamically controlled AV dedicated lane on the outermost motorway lane was predicted to increase the shared mobility rate the most in the long term, among the other AV dedicated lane scenarios.

Delphi results showed a short-term increase in the shared mobility rate due to the 'return to origin' and 'park outside' strategies under parking price policies as compared to the baseline scenario, which was further indicated to diminish at higher penetration of AVs. On the other hand, 'park inside' and 'drive around' scenarios were predicted to increase shared mobility with increasing automation as compared to the baseline scenario.

All parking space regulations scenarios in the Delphi study were foreseen by the experts to improve the shared mobility rate as compared to the baseline scenario. In particular, replacing on-street parking spaces with space for public use, driving lanes, or pick-up/drop-off parking spaces were estimated to increase the shared mobility rate by almost 47%, 13%, and 19%, respectively for 100% AVs market penetration rate.

The majority of experts predicted an increase in shared mobility rate due to automated ride sharing services compared to the baseline scenario as well as with increasing MPRs of AVs. However, at full fleet penetration of AVs, the experts indicated the impact to be the same under both baseline scenario and with automated ride sharing services.

Most of the experts' responses indicated a lower shared mobility rate in the case of GLOSA implementation as compared to the baseline scenario. With respect to the increasing automation rate, the majority of the experts predicted that implementation of GLOSA system increases the shared mobility rate from about 6 to 15%. However, around 17% of experts indicated no effect at all on shared mobility rate due to GLOSA system.

Vehicle utilisation rate

Vehicle utilisation rate was considered the percentage of time a vehicle is in motion (not parked). Overall, the majority of experts' opinions showed that the introduction of automation in the urban environment (baseline scenario) will lead to an increase in vehicle utilisation rate. This opinion is also reflective of the opinion on the amount of travel and changes in the modal split.

Under the road use pricing policies, most experts indicated that the given city toll scenarios will have a reduced effect on vehicle utilisation rate compared to the baseline scenario. However, with city toll scenarios, the vehicle utilisation rate would increase with increasing automation in the long term. Regarding the city toll scenarios, an increase of about 14% was indicated for empty km pricing. On the other hand, static and dynamic toll scenarios were estimated to increase vehicle utilisation rate by almost 15% and 18% was, respectively.

The Delphi results on AV dedicated lanes scenarios indicated an oscillating trend on vehicle utilisation rate with increasing AVs MPR; however, the vehicle utilisation rate was estimated to increase in the long term (at high MPRs). In particular, it was indicated that AV dedicated lane on the 'outermost motorway lane', 'innermost motorway lane' and 'outermost motorway lane and A-road' would increase vehicle utilisation rate in the long term by 27%, 19% and 21%, respectively.

The experts envisaged that with parking price policies, vehicle utilisation rate will increase with increasing automation. In this regard, AVs 'return to origin' scenario was predicted to impact the vehicle utilisation rate the most (by 42%) as compared to 'drive around' (40%),'park outside' (35%) scenarios. The smallest effect on the vehicle utilisation rate was estimated to be under 'park inside' scenario up to around 19%.

The majority of experts indicated that replacing on-street parking spaces with space for public use would increase vehicle utilisation rate in the short term only and would decrease in the long term. On the other hand, replacing on-street parking with pick-up/drop-off parking spaces would reduce vehicle utilisation rate in the short term and have almost no effect in the long term.

The experts indicated that the introduction of automated ridesharing services in the urban environment would lead to an increase in vehicle utilisation rate with increasing automation. However, the impact was indicated to be lesser as compared to the baseline scenario (increasing AVs only without automated ride sharing services). Most experts estimated the maximum increase was to be by almost 20% due to automated ride sharing services.

Most of the responses from experts indicated only a minor impact of GLOSA system on vehicle utilisation rate (up to 10% in the long term).

Vehicle occupancy

The impact of introducing AVs as well as the implementation of different policy interventions on vehicle occupancy (percentage of seats in use) was estimated through the Delphi study.

The results indicated mixed opinions related to the impact on vehicle occupancy due to increasing automation. Some experts indicated an increase in the long term while others predicted no significant impact to a slight reduction in vehicle occupancy with increasing MPRs of AVs.

According to most experts, city toll scenarios would increase vehicle occupancy compared to the baseline scenario with increasing MPRs of AVs. The introduction of static city toll and empty km pricing were both indicated to increase vehicle occupancy by 18%. On the other hand, the dynamic city toll scenario was estimated to have an even greater impact reaching up to by almost27% at 100% MPR of AVs.

All the AV dedicated lanes scenarios were indicated to have an increased impact on vehicle occupancy compared to the baseline scenario. Additionally, the experts were of the opinion that AV dedicated lane scenarios would increase vehicle occupancy in the long term. The AV dedicated lane on the outermost motorway lane and the dynamically controlled AV dedicated lane scenarios were indicated to increase vehicle occupancy by almost 17% and 19%, respectively. The AV dedicated lane on the outermost motorway lane and A-road was predicted to have the least impact on vehicle occupancy (almost 10%).

Most experts estimated a positive impact on vehicle occupancy due to parking price policies compared to the baseline scenario and under higher MPRs of AVs. The Delphi study results showed that vehicle occupancy can be increased up to 26% in the 'park inside' scenario. CAVs driving around scenario was predicted to slightly reduce vehicle occupancy in the short term and slightly increase at higher MPRs of AVs almost up to 5%. The 'return to origin' and 'park outside' scenarios were expected to cause an increase in vehicle occupancy in the long term by almost 10% and 19%, respectively.

The Delphi study results on parking space regulations showed that replacing on-street parking with spaces for public use or with pick-up/drop-off parking spaces would progressively increase vehicle occupancy with increasing automation reaching 19% and 14%, respectively, for 100% MPR of AVs. On the other hand, replacing on-street parking with driving lanes was indicated to reduce vehicle occupancy by around 10% at full fleet penetration.

According to most experts, the introduction of automated ridesharing in the urban environment would significantly increase vehicle occupancy as compared to the baseline scenario. With respect to increasing automation, the experts were of the view that the inclusion of automated ride sharing services will increase vehicle occupancy in the short term only, which will not be further affected in the long term.

Regarding the implementation of GLOSA system, the experts in the 1st round of the Delphi study indicated a general increase of about 6% in vehicle occupancy compared to the baseline scenario regardless of the MPR of AVs. However, in the 2nd round, almost 67% showed a slight agreement to the 1st round results while 17% showed complete disagreement indicating no impact of the GLOSA system on vehicle occupancy.

6 Conclusion and future work

Within this deliverable medium-term or system level impacts of CCAM services on passenger transport have been analysed through various applicable methods. The methodologies can be used for analysing future impacts due to various other policy interventions not covered in this deliverable. There is no real-world data available on fully automated vehicles and their performance, and we need better knowledge of CAVs behaviours. There are also challenges involved in testing fully automated vehicles under real-world traffic conditions. Within LEVITATE, an extensive literature review was performed in this regard based on theoretical, simulation based, and experimental studies on early level automated vehicles while also having made several necessary assumptions in the models. The results should be examined according to the assumptions used as well as the characteristics of the study networks.

6.1 Conclusions

Based on the results from the different methods and the discussions in the previous section, some key conclusions related to system level or medium-term impacts of CCAM on passenger transport can be drawn as follows:

- In general, increasing automation without any other policy intervention (baseline scenario) was estimated to progressively increase amount of travel, shared mobility rate, and vehicle utilisation rate. Transition phases or mixed fleet scenarios could potentially have adverse impact on congestion. Almost no or slight reduction can be expected in vehicle occupancy with increasing automation in the long term. Modal share of public transport and active travel are expected to both be negatively impacted with increasing MPRs of AVs.

- Travel distances were found to decrease with increasing automation as well as tolling levels, with the exception of dynamic tolling of the inner-city area. Due to increased comfort and direct access of passenger cars to most places, automated vehicles can potentially reduce the use of public transport modes. However, due to various road-use pricing policies, a shift to public transport can be expected. A maximum increase of 12 % was estimated due to the implementation of prohibitive tolling levels. Mesoscopic simulation results showed only a minor decline in the mode split of active travel for increased automation but increases in active modal share were found under tolling policies. System dynamics results were found to be in-line with mesoscopic findings and indicated increases in both public transport modal share as well as active travel due to road use pricing as compared with the baseline scenario.

- Based on the microsimulation results on dedicated lanes, the innermost lane placement of dedicated lane can potentially have added benefits in terms of improving network performance and safety. However, the most optimal strategy may differ based on the network characteristics and would require testing different strategies based on the test network.

- Compared to the baseline scenario, replacing on-street parking with driving lane, cycle lane and public spaces have shown better performance for both total distance travelled and delay indicators, compared with the interventions of removing half of the on-street parking spaces and replacing them with pick-up/drop-off spaces. However, replacing on-street parking with driving lanes can potentially have a strong impact on decreasing public transport modal split. The active travel modal split was found to be slightly increasing. The results suggest that removing half of the parking spaces would have a marginal effect on modal split for public transport but a positive impact on active travel, increasing up to 70% MPR and becoming insensitive with further increase in the fleet penetration.

- The parking price policies can potentially create additional delays in the system, reduce distance travelled and impact the overall network performance. 'Balanced' and 'heavy return to origin and park outside' strategies were found to have better performance than the 'drive around' strategy. Overall, 'balanced' parking strategy could potentially be beneficial both in terms of reducing potential negative impacts due to parking price policies as well as increasing active travel.

- Automated ride sharing services may negatively impact the network performance due to the increased number of trips and the empty VKT caused by making repositioning trips to reach new travellers. The adverse impacts on traffic could be reduced with increased willingness to share such services. However, with increased willingness to share and increasing MPR, the active travel can be negatively impacted.

- Implementation of the GLOSA system on multiple intersections along a corridor can provide added benefits in terms of reducing delays and improving traffic flow.

- An increase in vehicle utilisation rate and shared mobility with the introduction of automated vehicles can be expected as indicated by the experts. Whereas vehicle occupancy may not be significantly impacted just with automation. It is also predicted that vehicle occupancy, vehicle utilisation rate, and shared mobility will increase with the inclusion of dedicated lanes, parking pricing policies, as well as with the implementation of GLOSA system. An increase in shared mobility has also been predicted by the experts if on-street parking spaces are replaced with space for public use, driving lanes or with pick-up/drop-off spaces. With respect to vehicle utilisation rate, the Delphi findings suggest that replacing on-street parking with public space will increase vehicle utilisation rate in the short term only. The replacement with pick-up/drop-off spaces has been estimated to reduce vehicle utilisation rate in the short term whereas almost no effect can be expected in the long term.

The following table summarises the expected system level or medium-term impacts of CCAM (baselines) on the key variables considered in this deliverable – which might be desired or undesirable – and lists potential policy interventions (SUC) that could be applied to support positive or mitigate negative effects of CCAM.

Table 6.1: Expected medium-term impacts due to CCAM and recommended policy interventions

Impact variable	CCAM impact (increase/ decrease)	desired/ undesirable	Potential policy interventions (SUC) to support or mitigate
Congestion	increase in short term (transition phase)	undesirable	• dedicated CAV lanes on highways • parking space regulations • GLOSA
Amount of travel (passenger cars VKT)	increase	undesirable	• road use pricing
Modal split using public transport	decrease	undesirable	• road use pricing • automated ride sharing
Modal split using active travel	decrease (or neutral)	undesirable	• parking price policies • road use pricing • parking space regulations
Shared mobility Rate	increase	desirable	• road use pricing • parking price policies • parking space regulations • automated ride sharing
Vehicle utilisation rate	increase	undesirable	• Parking price policies • road use pricing
Vehicle occupancy	decrease (or neutral)	undesirable	• road use pricing • Parking space regulations • automated ride sharing

Due to the applied multi-method approach, some of the results, in particular for the baseline scenario where no interventions are applied, seem to be conflicting. Different methods and different sub-use cases have used different data sets and assumptions which makes part of the results difficult to compare. Nevertheless, the focus of results that are delivered to the PST is on the *relative* changes compared to the baseline of each model/ method – and these relative values were found to be consistent across methods where a comparison was possible.

These findings through the combination of methods used in this project present an overarching overview of a broad range of impacts, which can help identifying potential benefits and disbenefits due to various policies. Cities cannot control the introduction of CAVs into the transport system, but they can manage the potentially adverse impacts particularly during the transition phase.

6.2 Future work

An ongoing task is the integration of these results in the web-based policy support tool (PST) that will make the LEVITATE impact assessment framework user friendly for public authorities and transport planners. Future work in the project includes testing and analysing these impacts on different study areas to identify the variations and transferability of the findings. Additionally, combined effects due to different policy interventions, if implemented together, will be analysed through specific case studies.

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