Guidelines and recommendations for future policy of cooperative and automated passenger cars

Deliverable D6.5 – WP6 – PU

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824361.

Guidelines and recommendations for future policy of cooperative and automated passenger cars

Work package 6, Deliverable D6.5

Please refer to this report as follows:
Gebhard, S., Nabavi Niaki, M., Schermers, G , Goldenbeld, C. and Chaudhry, A. (2022). Guidelines and recommendations for future policy of cooperative and automated passenger cars, Deliverable D6.5 of the H2020 project LEVITATE.

Project details:	
Project start date:	01/12/2018
Duration:	42 months
Project name:	LEVITATE – Societal Level Impacts of Connected and Automated Vehicles
Coordinator:	Andrew Morris, Prof. of Human Factors in Transport Safety, Loughborough University Ashby Road, LE11 3TU Loughborough, United Kingdom
	This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824361.

Deliverable details:	
Version:	Final
Dissemination level:	Public
Due date:	30/11/2021
Submission date:	17/01/2022

Lead contractor for this deliverable:
SWOV

Report Author(s):	Gebhard, S., Nabavi Niaki, M., Schermers, G ,Goldenbeld, C. (all SWOV, Netherlands), Chaudhry, A (Loughborough)

Revision history

Date	Version	Reviewer	Description
21/12/2021	Preliminary draft 1	Wendy Weijermars (SWOV)	Accept with reservation

04/01/2022	Preliminary draft 1	Katherina Deliali (NTUA)	Accept
14/01/2022	Final draft	G Schermers (SWOV) Amna Chaudhry (Loughborough)	
17/01/2022	Final deliverable	Andrew Morris – Loughborough University ➔ EC	

Legal Disclaimer

All information in this document is provided "as is" and no guarantee or warranty is given that the information is fit for any particular purpose. The user, therefore, uses the information at its sole risk and liability. For the avoidance of all doubts, the European Commission and CINEA has no liability in respect of this document, which is merely representing the authors' view.

Table of contents

List of abbreviations

AUSS	Automated Urban Shuttle Service
ADAS	Advanced Driver Assistance Systems
AEB	Autonomous Emergency Braking
AV	Automated Vehicle
A2A	Anywhere-to-anywhere shuttle service
CACC	Cooperative Adaptive Cruise Control
CCAM	Cooperative, connected and automated mobility
CATS	Connected and Automated Transport Systems
CAV	Connected and Automated Vehicle
CCAM	Cooperative, Connected and Automated Mobility
C-ITS	Cooperative Intelligent Transport Systems
ERTRAC	European Road Transport Research Advisory Council
EU	European Union
FCW	Forward Collision Warning
FHWA	Federal Highway Administration
FORS	Fleet Operation Recognition Scheme
GDPR	General Data Protection Regulation
GLOSA	Green light optimal speed advisory
ISA	Intelligent Speed Assist
IVS	In-vehicle Signage
LCA	Lane Change Assist
LDW	Lane Departure Warning
LKA	Lane Keeping Assist
MPR	Market Penetration Rate
NHTSA	National Highway Traffic Safety Administration
NRC	National Research Council
PST	Policy Support Tool
SAE	Society of Automotive Engineers
SRG	Stakeholder Reference Group
SUC	Sub-Use Case
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to everything
VKT	Vehicle Kilometres Travelled

Technical definitions

Indicator	Definition or operationalisation (and relevance)
Amount of travel	The amount of travel is defined as the number of person (or vehicle) kilometres travelled in a year in a particular study area, region or country. This is generally a measure of mobility and reflects the total displacement of people, goods and vehicles in a given time period and region. This can be disaggregated to reflect for example specific modes or commodities. In Levitate we generally refer to person-km travelled. The amount of travel has an obvious relevance for transport policy and is a primary indicator of mobility. Changes in mobility needs impact on traffic safety, environment, accessibility, infrastructure provision and other policy domains.
Emissions	In Levitate the emissions are defined as the (total) amount of vehicle exhaust emissions and expressed by the amount of carbon dioxide (CO2), nitrogen oxides (NOX) and particulate matter (PM10) emissions in kilogrammes/km or kilotons. In the synthesis reports for WP5, 6 and 7, the focus is on carbon dioxide emissions although particulates and NOX are also briefly discussed.
Energy efficiency	Energy efficiency was defined as the average rate (over the vehicle fleet) at which propulsion energy is converted to movement (%).
Inequality of transport	The inequality in transport was defined as the degree to which transport services are used by socially disadvantaged and vulnerable groups including people with disabilities.
Modal split	Modal split (or modal share) describes the relationship between the means of transport (the modes) and the volume (number) of persons or commodities transported by each mode within a region. So, in effect it is the proportion of travellers using a specific type of transport. By modal split we typically refer to the percentages of people travelling on foot (walking); cycling; by bus, train or other public transport, in private cars etc. In freight transport we may distinguish on the basis of the mass (or volume) of specific (categories) commodities being transported by specific vehicle types. Modal split is one of the most essential inputs for transportation planning and modelling and is equally important for transport policies. For example, an increasing demand for travel by private cars in favour of public transport is generally enough incentive for decision makers to take steps to improve public transport or to discourage private transport through pricing or other disincentives.
Parking space	Parking space is defined as the required parking space in the city centre per person (m2/person).
Public health	Public health was operationalised as a subjective rating of public health state, related to transport.
Road safety	Within LEVITATE, road safety impacts were estimated from a combination of the AIMSUM microsimulation using the Surrogate Safety Assessment Model (SSAM), estimates of crashes involving vehicles and vulnerable road users and other secondary impacts. In the microsimulation estimates crashes involve only motorised vehicles (cars, buses and trucks) whereas crashes involving vulnerable road users (cyclists and pedestrians) were estimated from accident statistics, based on data from Austria and

Indicator	Definition or operationalisation (and relevance)
	Vienna. In the estimation of road safety impacts crashes for motorised traffic (from SSAM) were expressed as crash rates (crashes per 1000 veh-km) and for crashes involving vulnerable road users as absolute numbers. For both these the effect on CAV introduction was expressed as a percentage change.
Shared mobility rate	The shared mobility rate in Levitate is defined as the proportion of trips that are made by persons sharing a particular mode of transport with others and is a proxy to vehicle occupancy. This aspect is also relevant for transport policy particularly where large numbers of private cars are used to transport relatively low numbers of people. Influencing vehicle occupancy may hold significant benefits for reducing the demand for road space by reducing the number of vehicles. This has significant benefits for all policy domains.
Vehicle utilization rate	Within Levitate the vehicle utilisation rate is considered as the percentage of time a vehicle is in motion (not parked). Vehicle utilisation is particularly relevant for freight and public transport vehicle operators where vehicles need to be optimally utilised to minimise operating costs. For road authorities this is an indicator for, for e.g., the demand for parking versus the demand for road capacity.

About LEVITATE

Societal Level Impacts of Connected and Automated Vehicles (LEVITATE) is a European Commission supported Horizon 2020 project. It has as objective to prepare a new impact assessment framework to enable policymakers to manage the introduction of connected and automated transport systems, to maximise the benefits and to utilise these technologies to achieve societal objectives.

Connected and automated transport systems (CATS), or recently the more accepted term 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 traffic 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 forecasting the impact of future systems represents a major challenge. The dimensions for assessment are themselves quite broad ranging from impacts on traffic safety to the environment and potentially including sub-divisions within the domains which adds 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 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 back casting methods to identify the sequences of CCAM measures that will result in their desired policy objectives.

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, LEVITATE seeks to forecast societal level impacts of connected and automated transport systems (CATS) or, as these systems are more recently referred to, cooperative, connected, and automated mobility (CCAM). These impacts include effects on mobility, safety, environment and economy. Work Package 6 (WP6) considers the societal impacts of automated passenger car use in urban environments. Within WP6, the impacts of six policy measures related to particular developments in automated passenger cars are considered in what are termed sub-use cases (SUCs).

The goal of this Deliverable is to summarize the more detailed results presented in deliverables D6.2-D6.4 (Haouari, et al., 2021; Sha, et al., 2021; Chaudhry et al., 2021), to provide an overview of the main expected trends for each of the quantified impacts (e.g. emissions, congestion). Four methods were employed to quantify the future impacts of connected and automated vehicles: microsimulation, mesosimulation, system dynamics, and Delphi. Estimates derived from the microsimulation are based on models from the road networks in three European cities: Manchester, Santander and Leicester. The mesosimulation and system dynamics models are based on road networks from the city of Vienna, and the Delphi survey is not location-specific and relies on consensus-based estimates of a group of experts in the topic field. The methods were applied based on their strengths and capabilities to derive different impacts of an increasing penetration rate of CAVs within the total vehicle fleet, together with the deployment of each of the following six passenger car sub-use cases (SUCs):

- **Provision of dedicated lanes for CAVs** *(microsimulation, Delphi)*
- **Replace on-street parking with other facilities** *(microsimulation, system dynamics, Delphi)*
- **Road use pricing** *(mesosimulation, system dynamics, Delphi)*
- **Parking price regulation** *(microsimulation, system dynamics, Delphi)*
- **Green light optimal speed advisory (GLOSA)** *(microsimulation, Delphi)*
- **Automated ride sharing** *(microsimulation, system dynamics, Delphi)*

For each of these six SUCs, several implementation scenarios were estimated, varying for example the type of road use pricing (static or dynamic) or the various alternatives which may replace on-street parking (e.g. a driving lane or public space). For each impact, a baseline scenario is estimated; the baseline scenario refers to a “no intervention” scenario, representing the expected transition (autonomous development) of vehicle operations from human-dependence to fully automated vehicles. Any additional effect of the SUC interventions can be determined by comparing the baseline situation for a given penetration rate with the specific SUC results; the difference between the baseline and the SUC is the added effect produced by implementing the specific SUC intervention in the simulated network.

Approach to summarizing LEVITATE results

To summarize the many results from the three deliverables of Work Package 6 (Haouari, et al., 2021; Sha, et al., 2021; Chaudhry et al., 2021), a selection of sub-use case scenarios are presented in overview tables with their predicted trend for each of the considered impacts. Depending on the sub-use case, this meant excluding some scenarios from the overview which provided similar insights to other scenarios (e.g. lower demand shares within automated ride sharing) or represented less realistic extremes (e.g. cars not parking and remaining on the roads due to parking price regulation). For some sub-use cases, an average is taken of a few scenarios which consist of small variations of the same intervention and show similar results (e.g. different placements of a dedicated lane for the UK context). An average was chosen in order to 1) provide a more generalised trend for the SUC less specific to the simulation parameters and 2) due to the largely similar results between scenarios suggesting an overarching trend regardless of scenario. In addition, for some impacts where estimates are calculated by both a simulation/modelling method (microsimulation, mesosimulation, system dynamics) as well as the Delphi survey, Delphi results are excluded from the overview due to the other methods being considered the more rigorous methods within LEVITATE.

The predicted trends for each sub-use case scenario are quantified in terms of percentage changes reported across an increasing market penetration rate of connected and automated vehicles (CAVs) in the network vehicle fleet (see *Figure 1* below). For each impact, the overview tables distinguish between the:

- Baseline development (no intervention): the expected development as the proportion of CAVs in the traffic network increases to 100%
- Intervention-based development (SUC): the expected development of the same impact when both the sub-use case intervention and increasing penetration levels of CAVs are at work

As illustrated in *Figure 1*, the percentage change takes the first stage of the baseline scenario as the reference point (zero percentage change). At this starting point of the baseline, no intervention has been implemented and no automated vehicles are present in the network (0% penetration of CAVs). The development of impacts (expressed as percentages indicating a decrease or increase from the initial value) under the baseline indicates the sole expected effect of increasing CAV penetration in total traffic. The development of impacts under the intervention-based condition indicates the expected effect of the combination of the SUC intervention and the growing automation level. The specific effect or impact of the SUCs can be determined by comparing the baseline situation for any given penetration rate with the specific SUC results; the difference between the baseline and the SUC is the added effect produced by implementing the specific SUC intervention in the simulated network.

Because of differences between the four studied cities' road networks and traffic conditions, as well as differences in each methodology's assumptions and scale, impact estimates across methods and cities can vary. This also results in variations in the baseline estimations for a given impact, depending on the city/method applied. Generalising the specific results is therefore not advised unless these are applied to similar conditions as adopted in Levitate. However, the estimates within and across methods and cities are indicative of expected trends for the SUCs tested.

Figure 1: Illustration of overview tables

		Increasing penetration rates of automated vehicles (CAVs) in traffic							
		100% human-driven vehicles	▸						100% automated vehicles
		1	2	3	4	5	6	7	8
Impact (e.g., emissions, road safety, congestion)	Baseline – no intervention	0% (reference)	% change	% change	% change	% change	% change	% change	% change
	Intervention (sub-use case)	% change	% change	% change	% change	% change	% change	% change	% change

Findings

The main findings from the work done in WP6 on expected developments from the six major SUCs and the various scenarios are presented below. It should be noted that the impacts of some of the SUCs have been estimated using one or more of the different methods: microsimulation, mesosimulation, system dynamics and Delphi method. The microsimulation method was applied to 5 sub-use cases, the mesosimulation was appropriate to evaluate 1 sub-use case, the system dynamics method was utilized to evaluate 4 of the sub-use cases, while the Delphi method was applied to all 6 sub-use cases. The four different methodologies (microsimulation, mesosimulation, system dynamics, Delphi) were also each used to calculate a different set of mobility, environmental and societal/safety/economic impacts depending on the method's characteristics (e.g. microsimulation is more suitable to small-scale traffic analysis while mesosimulation and system dynamics take systemic/wider impacts into account). Some impacts were calculated by multiple methods (but as explained earlier, not all are presented in this synthesis). In *Table 1*, the impact definitions and methodologies are described.

Table 1: Illustration of overview tables

Policy area	Impact	Definition	Methodology
Environ-ment	CO_2 emissions due to vehicles	*Concentration of CO_2 pollutants as grams per vehicle-kilometre (all road traffic)*	Microsimulation
	Energy efficiency	*Average rate (over the vehicle fleet) at which propulsion energy is converted to movement (all road traffic)*	Delphi
Mobility	Travel time	*Average duration of a 5 Km trip inside the city centre (all traffic)*	Microsimulation/ Mesosimulation
	Access to travel	*The opportunity of taking a trip whenever and wherever wanted (10 points Likert scale)*	Delphi
	Amount of travel per person	*Kilometres of travel per person in an area (all traffic)*	Mesosimulation
	Total kilometres travelled	*Total vehicle kilometres travelled in the network (all traffic)*	Microsimulation
	Congestion	*Average delays to traffic (seconds per vehicle-kilometre) as a result of high traffic volume (all traffic)*	Microsimulation
	Modal split: Active travel	*% of network trip distance (all traffic) made using active (walking, cycling) transportation*	Delphi / System dynamics
	Modal split: Public transport	*% of network trip distance (all traffic) made using public transportation*	Delphi / System dynamics
	Shared mobility rate	*% of trips made sharing a vehicle with others*	Delphi
	Vehicle utilisation rate	*% of time a passenger vehicle is in motion (not parked)*	Delphi

	Vehicle occupancy	*% of kilometres a vehicle is occupied by passengers*	Delphi
Society, safety, economy	Vehicle operating cost	*Direct outlays for operating a vehicle per kilometre of travel averaged over all traffic*	Delphi
	Parking space demand	*Required parking space in the city centre per person*	Delphi / System Dynamics
	Road safety	*Number of predicted crashes per vehicle-kilometre driven (all traffic)*	Microsimulation
	Public health	*Subjective rating of public health state, related to transport (10 points Likert scale)*	Delphi
	Accessibility of transport	*Degree to which transport services are used by socially disadvantaged and vulnerable groups incl. people with disabilities (10 points Likert scale)*	Delphi
	Average commuting distance	*Average length of trips to and from work (all traffic)*	System Dynamics

Baseline developments

The increasing penetration levels of connected and automated vehicles (CAVs) in the urban city area is estimated (for most baselines) to have a positive impact on the **environment** (less emissions, higher energy efficiency), on **society, safety & economy** (improved road safety, public health, and lower vehicle operating costs) and on most **mobility** indicators (more access to travel and less congestion). In the absence of policy interventions, some potentially negative effects could be realised if private automated vehicle transport leads to a decline in walking, cycling, and/or public transport trips.

The impacts for the various SUC are measured relative to the baseline starting point: the situation with no intervention or presence of automated passenger cars. Important to note is that baseline estimated vary across methods and the city networks to which CAVs and the SUCs were applied. In the microsimulation, results for the baseline estimates differ between SUCs due to different networks being studied for each SUC. For the mesosimulation and system dynamics impacts, one baseline was calculated for the entire city of Vienna, which may also show different effects from the networks used in the microsimulation. Also the baseline estimates in the Delphi method differ across SUCs because different expert groups evaluated different SUCs. The results therefore reflect the implementation of CAVs under a wide range of conditions, networks, and methodologies. The results serve as indicative of impact ranges rather than definitive estimates, which would have required a much larger study as well as more observational data which is unavailable due to the early stages of automated technology. Care must be taken in generalising the results to situations to those which are comparable to those modelled in Levitate. The results are transferable in as far as they are applied to networks that are comparable to those used in Levitate (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021).

The following points summarise the primary baseline results:

- Environment: For the **CO_2-emissions**, in all five sub-use case networks a substantial positive baseline development was estimated, even at low levels of CAV penetration (CO_2 emissions reduction of 20% at 20% CAV penetration rate). This is due to the assumption that all CAVs are electric vehicles. Out of the six estimated baseline scenarios for the development of **energy efficiency**, all expert groups predicted that energy efficiency will improve once CAV penetration exceeds 60% (5% to 31% improvement at full penetration). For two of these baseline estimates, a slight initial decrease in energy efficiency is predicted at low CAV penetration rates.

- Mobility: For the mobility domain, on the positive side most (4 out of 5) baselines predict a reduction of **congestion** (between 9% and 13% reduction), most predict an increase in **shared mobility rates** (between 11% and 41% increase at 100% CAV penetration level), and most baselines predict an increase in the **vehicle utilisation rate** (four out of the six baselines estimate an increase between 43% and 50% increase at 100% CAV penetration level). However, on the negative side, most baselines in both the Delphi study and system dynamics model predict a reduction in the **modal split of active transportation** (between 13% and 56% reduction at 100% CAV penetration level) and **public transport** (between 10% and 29% reduction at full automation) in favour of CAVs. For **total kilometres travelled, travel time** and **vehicle occupancy rates,** different baselines produce very different results; there seems to be no clear pattern for these impacts.
- Road safety: Regarding **safety**, for all the baseline networks, a substantial improvement in road safety is predicted at full penetration of automated vehicles (67% to 92% reduction in crash rates of crashes between passenger vehicles). At lower penetration rates when there is still mixed traffic on the road, the impact on crash rates is more gradual. For three out of the five baselines, an improvement in road safety is already clear with the presence of 40% CAVs on the road (11% to 25% reduction in crash rate). For the other two baseline networks (Santander and the GLOSA network from Manchester), a temporary increase in crash rates is predicted in low penetration rates when many human-driven vehicles are still on the road. This is likely due to interactions between human-driven vehicles and CAVs, whose different driving styles may cause some additional conflicts. Once human-driven vehicles are no longer on the road, all baselines show a large decrease.
- Society/Economy: Most baselines (5 out of 6) predict an improvement in **public health** (2% to 12% improvement), and all 6 baselines predict an improvement in **equal accessibility of transport** (mostly between 4% and 25%). Effects on **vehicle operating costs** are mixed as CAV penetration increases to 100% (-20% to +13%), but at lower penetrations (20% to 40% CAVs) all baselines predict vehicle operating costs to at least temporarily increase. The results for **parking space demand** estimated by system dynamics predict parking space demand to increase as CAVs become more widespread. This is due to a predicted mode shift towards private automated vehicle travel from other modes (e.g. public transport), thus increasing the demand for parking if no further policy measures are taken.

The effect of the SUC interventions

Below is a summary of the findings from the six major sub-use cases and their implementation scenarios:

1. Road use pricing**:** Road use pricing is expected to lead to a number of additional benefits over the baseline impacts: better **energy efficiency** (dynamic toll more than static toll or empty km pricing), less reduction in the use of **active modes** and **public transport**, higher **vehicle occupancy** rate, and lower **parking space demand**. On the negative side, road use pricing is expected to lead to increase in **vehicle operating costs**, and **less equal accessibility of transport**. The scenario "empty km pricing” is expected to contribute more positively towards keeping vehicle operating costs within bounds compared to the “static toll” and “dynamic toll” scenarios. The “static toll” scenario is expected to result in the highest shares in active transport modes and public transport. The “dynamic toll” scenario is expected to lead to the highest vehicle occupancy rates.

2. Dedicated CAV lanes: Compared to the baseline, dedicated lanes for CAVs do not make a clear difference for emissions, travel time, kilometres travelled, and road safety. On the positive side, dedicated lanes are expected to lead to better **access to travel** when lanes are "dynamic," slightly reduced **congestion** in mixed human-driven/CAV traffic, a higher **vehicle utilisation** rate, higher **vehicle occupancy** rate, and lower **vehicle operating costs**. The "dynamic" lanes scenario performs better than the "fixed" lane scenarios in terms of improvements on energy efficiency, access to travel, vehicle occupancy rate, vehicle operating costs, and in terms of a lesser decrease of the active mode share.

3. Parking price regulation: Parking price regulation does not seem to make a noticeable difference on CO_2 emissions or shared mobility rate. On the positive side, parking price regulation is expected to compensate some of the negative impacts of CAVs on the **mode share of public transport** and **active modes**, resulting in more walking, cycling and public transport use than in the baseline development. However, in both cases these interventions cannot overcompensate for the negative impact that CAVs are expected to cause to the modal share of public transport and active modes. Less private vehicle use than in the baseline also results in a reduced demand for **parking space**, according to the system dynamics model. The alternative parking behaviours resulting from parking price regulation are predicted to have some potentially negative (or less positive) effects compared to the baseline development on: **energy efficiency**, **travel time** and **congestion**, and **road safety**. However, these negative effects predicted by microsimulation and Delphi do not take into account the effects on modal split predicted by system dynamics which may counteract these effects to a certain degree if private vehicle transport is reduced. Reduced benefits are also predicted for **access to travel**, **equal accessibility of transport**, **vehicle utilisation rate**, and **vehicle operating costs**, due to the increased costs of parking in central locations.

4. Replacing on-street parking: The interventions aimed at **replacing on-street parking** show similar results to the baseline (no added effect) in terms of CO_2 emissions. Positive effects on mobility in terms of reduced **travel time** and **congestion** are predicted due to the reduction in parking manoeuvres. For many of the impacts, the effect of replacing on-street parking was dependent on the scenario: removing half of spaces, replacing with driving lanes, replacing with pick-up/drop-off spaces for shared CAVs, or replacing with public space or cycling lanes. Replacing with "public space" was found to be particularly beneficial for **energy efficiency**, **shared mobility rate**, **modal splits of active** and **public transport**, **vehicle occupancy rate**, **vehicle operating cost**, **road safety**, and **public health**, but negative in terms of **access to travel.** Meanwhile, replacing on-street parking with "driving lanes" is expected to improve **access to travel** and use of **active modes** (to a lesser degree than public space), but reduce the mode share of **public transport** and negatively impact **public health** and **parking space demand**. The scenario "pick-up/drop-off" generally performs worse than the other scenarios in terms of **energy efficiency, travel time**, **kilometres travelled, congestion**, shares of **active transport modes** and **public transport**, **shared mobility rate**, and **road safety**. On the positive side, the "pick-up/drop-off" scenario is expected to result in better results for **access to travel** and **equal accessibility of transport** than the other scenarios in the replacing on-street parking SUC.

5. Automated ride sharing: Automated ride sharing does not make a noticeable difference for CO_2 emissions or parking space demand. Compared to the baseline, extra benefits are expected in terms of **energy efficiency**, **access to travel**, **public transport use**, **shared mobility rate** (at lower CAV penetrations), **vehicle occupancy rate**, and **vehicle operating costs**. Compared to the baseline, it has a negative impact on **congestion** (due to empty vehicle kilometres needed to reposition vehicles), **travel time**, use of **active modes**, and **vehicle utilisation rate**. The impact on **road safety** is mixed: at low CAV penetrations, automated ride sharing improves safety by serving a share of otherwise human-driven trips. However, as all trips become automated the added benefit reduces and the extra congestion caused by ride sharing rather serves to slightly increase crash rates compared to the baseline at high penetration rates. Furthermore, the impacts of automated ride sharing depend on what share of the users are willing to share trips with other users. When willingness to share is low (20% scenario), less positive results are predicted for mobility and road safety due to the larger number of trips and vehicles needed to serve the demand (travel time and congestion increase; kilometres travelled and road safety decrease).

6. GLOSA: The **GLOSA** sub-use case is associated with no noticeable additional impacts on CO_2 emissions or kilometres travelled. Compared to the baseline it shows positive impacts on **travel time**, **congestion**, **public transport use**, **road safety**, and **vehicle operating costs**. A negative (or less positive) impact compared to the baseline is predicted for **access to travel**, **active mode share**, **shared mobility rate**, **vehicle utilisation rate**, **public health**, and **equal accessibility of transport**.

Overall conclusions

In summary, the following primary conclusions were drawn:

- Increasing penetration levels of connected and automated vehicles in the urban city area are estimated (for most **baselines**) to have positive impacts on the environment (less emissions, higher energy efficiency), on society and economy (improved road safety, public health, and lower vehicle operating costs) and on mobility (more access to travel and less congestion). The predicted decrease in the modal share of public transport, walking and cycling in favour of automated passenger cars, however, may lead to some undesirable effects (such as the predicted increase in demand for parking space) without further policy measures.
- **Road use pricing** is expected to lead to a number of benefits above baseline developments, especially regarding mobility and environmental concerns: better energy efficiency, less reduction of active mode share, higher vehicle occupancy rate, less negative impact on public transport mode share, and less parking demand. On the negative side, road use pricing is expected to lead to an increase in vehicle operating costs, and lower accessibility to transport.
- **Dedicated CAV lanes** are predicted to have limited additional impacts on most indicators. Slight benefits were estimated for congestion, vehicle operating costs, vehicle utilisation and occupancy rates, as well as public health.
- **Parking price regulations** causing CAVs to return to other locations to park or drive around while waiting for passengers showed mixed results. Some negative effects are predicted on mobility (e.g. congestion), as well as the environment (energy efficiency), road safety, public health and accessibility of transport. These negative effects are primarily due to extra empty vehicle kilometres needed to reposition vehicles after

passenger drop-off. However, increased parking costs also have the potential to stimulate a moderate mode shift away from private vehicle transport, which may benefit use of active modes of travel and decrease the demand for parking space. Results regarding the effects on public transport use are mixed.

- Of the six major sub-use cases, **replacing on-street parking** is associated with a wide range of positive benefits over the baseline, including a large improvement in traffic conditions (reduced travel time and congestion), more positive development in active mode share, more shared mobility, better development of road safety and lesser demand for parking space. The facilities chosen to replace on-street parking also influence the impacts. Replacing on-street parking with public space is particularly associated with societal and environmental benefits (e.g. road safety, public health, energy efficiency) and is beneficial for shared, public, and active forms of mobility. Replacing on-street parking with driving lanes or pick-up/drop-off points is generally associated with lesser benefits, except for improved access to travel. Pick-up/drop-off points or removing only half of spaces also reduce the benefits to congestion due to maintaining some of the parking manoeuvres.
- **Automated ride sharing** is expected to benefit vehicle sharing, accessibility, and energy efficiency. While it is predicted to attract a moderate mode shift away from private vehicle transport, automated ride sharing is also predicted to attract trips away from walking and cycling. Furthermore, the additional empty vehicle kilometres necessary to reposition the vehicles to pick up their next passengers may lead to an increase in congestion, counteracting the benefits of the trips which can be shared. The impact of an automated ride sharing system is also dependent on the population's willingness to share trips with other travellers: a higher willingness to share is associated with less negative effects on congestion and marginally better road safety.
- **GLOSA** is not predicted to have large additional impacts on most indicators. Slight benefits to the traffic conditions are predicted (reduced congestion and travel time) as well as less decrease in public transport use and reduced vehicle operating costs. Potential negative effects on shared mobility rate, active travel, vehicle utilisation and occupancy rates, access to travel and public health are predicted. These negative effects may be due to a predicted increase in private vehicle travel with implementation of GLOSA.
- The policies considered in the SUCs have little additional impact on generated emissions; the large, expected reductions are primarily driven by the transition to CAVs which are assumed to be electric vehicles. The large, expected improvements in road safety with increasing automation are also driven by behavioural differences in CAVs (e.g. quicker reaction times) compared to human-driven vehicles, which is impacted minimally by SUC policies.

Sub-use case related recommendations

- Automated vehicles may provide benefits such as additional comfort, efficiency, the potential for multitasking, and accessibility to travellers who are not able to drive a vehicle themselves. This may cause a potential modal shift from other modes of travel (e.g. public transport, cycling, walking) towards private vehicle travel, which may be undesirable to cities for a number of reasons (e.g. energy usage, public health, use of public space). In order to limit potential increases in private vehicle transport, road use pricing, replacing on-street parking with public space, and parking price regulation may be useful policy measures.
- Replacing on-street parking with public space is predicted to be associated with more benefits than replacing the space with driving lanes, provided care is taken that sufficient accessibility is retained.

- The benefits of an automated ride sharing system are highly dependent on the users' willingness to combine trips and it has the potential to increase congestion due to empty repositioning trips. Therefore, the suitability of local conditions for an automated ride sharing system should first be studied before implementation.
- GLOSA is associated with some moderate benefits to traffic conditions, although more efficient traffic flow may also attract more private vehicle use. Therefore, GLOSA may be best paired with other measures to encourage practices such as vehicle sharing and active travel.

Strengths and limitations of Levitate

The followings observations pertain to strengths and limitations of research within WP6 LEVITATE. A potential *strength* of the LEVITATE project is that both smart city transport policy interventions and the associated impacts have been selected by a diverse group of stakeholders. A wide variety of impacts were studied at the same time and the project tried to capture interdependencies. The best available methods - microsimulation, mesosimulation, Delphi, and other complementary methods such as system dynamics and operations research - were used to study and quantify the expected impacts of mobility interventions intended to support CAV deployment and sustainable city goals. Within LEVITATE project these impacts provide essential input for developing a practical Policy Support Tool for city policy makers.

Concerning *limitations*, it should be pointed out there are general scientific difficulties in predicting impacts of connected and automated mobility due to uncertainties about propulsion energy, future capacity of power grids, employment, development of costs, and about the behaviour and acceptance with regard automated vehicles. The results of the models in LEVITATE are dependent upon specific assumptions. The simulation models used examined only two CAV profiles (aggressive vs. cautious); future work may extend the number of profiles. The safety results of the microsimulation did not include crashes where vulnerable road users are involved.

Given the many uncertainties in prediction, it is obvious that any predicted values are associated with large uncertainty. For WP6, it was decided not to include estimates of confidence intervals based on the standard error, derived from repeated trail runs of models, as a standard output since these intervals would be broad and non-informative. Also, the estimation of these intervals would tend to be biased in itself since the input variables and assumptions in the models are very likely much stronger determinants of predicted values than the variability in sample runs.

1 Introduction

Vehicle automation technology is expected to impact many areas of society. Highly automated vehicle technologies, complying to SAE levels 4 and higher, are expected to stimulate new innovations and policy interventions across the transport sector. These could include, for example, new vehicle types, new transport services and changes to infrastructure. The LEVITATE project is directed at studying—and where possible, quantifying—the expected impacts of vehicle automation on society and on mobility, safety, the environment, and the economy. This report provides a synthesis of the results achieved in Work Package 6 which studied the impacts of six sub-use cases within the broader domain of automated passenger cars. This specific chapter introduces the general scientific approach and methodology adopted by LEVITATE. Furthermore, it describes the aims of and Work Package 6 and provides an overview of the structure of the report.

1.1 General Levitate approach

Within LEVITATE, a range of cooperative, connected, and automated mobility (CCAM) applications and interventions are studied under three use cases: **automated urban transport**, **automated passenger cars** and **automated freight transport**. These correspond to Work Packages (WP) 5, 6 and 7.

In each Work Package, a stakeholder reference group workshop was organised among city administrators, industry representatives and transport specialists to gather views on the future and impacts of CCAM on these three primary use cases. Part of the workshop aimed at identifying specific developments, applications, or policy interventions within each sector (or use case). These were termed sub-use cases. Within LEVITATE, these lists were subsequently prioritized and refined in order to inform the interventions and scenarios related to urban transport, passenger cars or freight transport. The prioritisation of the sub-use cases mainly took three input directions into account: the scientific literature; roadmaps detailing the deployment of CCAM; and a workshop among stakeholders. This resulted in 13 sub-use cases covering 3 use cases as listed in *Table 1.1*.

Table 1.1: Sub-use cases (SUCs) investigated in LEVITATE.

Urban transport (WP5)	Passenger vehicles (WP6)	Freight transport (WP7)
Point to point automated urban shuttle service connecting two modes of transport	Provision of dedicated lanes for CAVs	Automated urban freight delivery
Point to point automated urban shuttle service in a large-scale network	Replace on-street parking with other facilities	Automated freight consolidation
On-demand automated urban shuttle service	Road use pricing	Hub to hub automated delivery
Last mile automated urban shuttle service	Parking price regulation	
	Green light optimal speed advisory (GLOSA)	
	Automated ride sharing	

Within LEVITATE, the impacts of the cooperative, connected and automated mobility (CCAM) sub-use cases are evaluated at three impact levels: direct, systemic, and wider. Direct impacts are changes that are noticed by each road user on each trip (Elvik et al., 2020). These impacts are considered as short-term and can be measured directly after the introduction of an intervention or technology, such as changes in travel time or costs. Systemic impacts are system-wide impacts within the transport system which are typically secondary effects resulting from direct impacts. These include measures such as congestion or modal split. These are considered as mid-term impacts. Wider impacts are those aspects on which transport systems rely to make mobility possible and those which are in essence a by-product of mobility. Examples of wider impacts are changes in land use and employment, energy demand and public health. These are inferred impacts measured at a larger scale and are the result of direct and system wide impacts. They are considered as long-term impacts (Elvik et al., 2020). *Table 1.2* presents the impacts considered within WP6, their impact level and the policy area(s) to which they are most related.

Table 1.2: Overview of (estimated) impacts in relationship to policy, scale, term and method.

Quantified impacts see D6.2-6.4 (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021)	**Impact level** see D3.1 (Elvik et al., 2020)	**Relevant policy areas**
Travel time	Direct	Mobility
Vehicle operating cost		Society, economy
Access to travel		Mobility, society
Congestion	Systemic	Mobility, society
Total kilometres travelled		Mobility, society
Amount of travel per person		Mobility, society
Modal split of travel using public transport		Mobility, society
Modal split of travel using active travel		Mobility, society
Shared mobility rate		Mobility, society
Vehicle utilisation rate		Mobility, society
Vehicle occupancy		Mobility, society
Demand for Parking	Wider	Mobility, society
Road Safety (crash rate)		Safety
Energy Efficiency		Environment, economy
Emissions		Environment
Public Health		Society
Inequality in Transport		Society
Commuting Distances		Mobility, society

LEVITATE considers the impacts of two simultaneous developments: an expected growth in the popularity of connected and automated vehicles (CAVs) over time (autonomous development driving the penetration of CAV technology), as well as the policy interventions defined in the sub-use cases. These are specified in terms of scenarios, for which the impacts in *Table 1.2* are estimated:

- **Baseline scenario:** growing penetration of connected and automated vehicles (CAVs) WITHOUT a policy intervention

- **Sub-use case scenarios:** growing penetration of connected and automated vehicles (CAVs) WITH a policy intervention implemented in the network (see *Table 1.1*)

For all scenarios it is assumed that the percentage of CAVs in the vehicle fleet will increase over time and that CAVs will be SAE level 5 (fully independent of human drivers). As the exact timescale of SAE level 5 vehicle development and adoption is still undefined, this expected growth is quantified in so-called "deployment scenarios" with varying market penetration rates of CAVs (see *Table 1.3*). These penetration rates reflect the transition from a driver-dependant vehicle fleet (100% human-driven vehicles) to a driverless vehicle fleet (0% human-driven vehicles).

In addition, two types of CAVs are distinguished in the deployment scenarios to represent an expected evolution in technology (*Table 1.3*). Within LEVITATE, first-generation automated vehicles have been defined as vehicles with limited sensing and cognitive ability. When compared to human driven vehicles, these 1st generation CAVS are assumed to have longer headways (following gaps), earlier anticipation of lane changes and longer reaction times (more time required in give way situations). Second generation automated vehicles have been defined as having advanced sensing and cognitive ability utilising data fusion usage allowing greater confidence in taking decisions, shorter headways (small following gaps), earlier anticipation of lane changes than human driven vehicles and less time in give way situations (Haouari et al., 2021). As less is known about the development of freight CAVs, only one type of automated freight vehicle is distinguished which adopts similar behaviour to 1st generation CAVs. These differences in driving style are implemented within the microsimulation models used in the impact quantification in WP6. The behavioural parameters chosen for 1st and 2nd generation CAVs in the microsimulations are explained in full in Appendix B.

Table 1.3: CAV Baseline deployment scenarios used within LEVITATE

Type of vehicle	Deployment scenarios							
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Human-Driven Vehicle	100%	80%	60%	40%	20%	0%	0%	0%
1st generation CAV	0%	20%	40%	40%	40%	40%	20%	0%
2nd generation CAV	0%	0%	0%	20%	40%	60%	80%	100%
Human-driven freight vehicle	100%	80%	40%	0%	0%	0%	0%	0%
Freight CAV	0%	20%	60%	100%	100%	100%	100%	100%

1.2 Work Package 6

Work Package (WP) 6 considers the specific case of passenger cars which are used across the transport system, mainly urban but extending to rural and highways. Work undertaken 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 CCAM on passenger cars. Findings complement those of WP5 (Urban transport) and WP7 (Freight) and feed into developing the LEVITATE Policy Support Tool (PST) in WP8. More specifically, the purpose of WP6 is to:

- identify how each area of impact (safety, environment, economy, and society) will be affected by the transition of human driven passenger cars into (driverless) connected and automated mobility (CCAM).
- assess the short-, medium- and long-term impacts, benefits, and costs of cooperative and automated driving systems for passenger cars.
- test interactions of the examined impacts in passenger cars, and
- prioritise considerations for a public policy support tool to help authority decisions.

Work Package 6 consists of five Deliverables in total (see *Table 1.4)*, covering the initial exploration phase (6.1), quantification of the impacts using four methodologies (6.2-6.4), and a final synthesis of the main results and policy relevance (6.5). More specifically, the purpose of this Deliverable (6.5) is to summarise the results of the short-, medium- and long-term effects of automated passenger cars and their impacts on society, economy, environment, and safety as presented and discussed in Deliverables 6.2-6.4 (Haouari, et al., 2021; Sha, et al., 2021; Chaudhry et al., 2021).

Table 1.4: Methods used to evaluate and quantify the expected impacts of automation within the urban transport sector

Goal	Method	Explanation	Deliverable
Exploration	Literature review	Existing literature on CCAM/CAVs/ADAS	6.1
	Stakeholder workshop	A group of key stakeholders – international/ twinning partners, international organisations, road user groups, actors from industry, insurances and health sector support the project and participated in workshops	6.1
Quantifi-cation	Delphi study	The Delphi method was used to determine those impacts that cannot be defined by the other quantitative methods	6.2, 6.3, 6.4
	Traffic micro-simulation	AIMSUN microsimulation of traffic at the city-district level (based on modelling individual vehicles)	6.2, 6.3, 6.4
	System Dynamics	Investigates several longer-term impacts which cannot be covered by other methods. Consists of 3 interacting sub-models: 1. A Transport Model modelling travel demand and trips 2. A population model used to calculate demand (which also calculates the average commuting distance) 3. A Public Space model based on modelling public space at a zone level, distinguishing between parking space, driving lanes and other uses. The relative demand for parking space is calculated in this model (see Sha et al., 2021b)	6.3, 6.4
	Traffic meso-simulation	MATsim activity-based modelling of behaviours and choices of individuals (based on groups or streams of vehicles) at the city level	6.2, 6.3

Synthesis & discussion	Synthesis	Major impacts summarized for the policy areas Environment, Mobility and Society/ Economy/ Safety	6.5
	Policy considerations	Recommendations & considerations for policymakers based on the wider literature	6.5

1.3 Purpose and structure of report

The purpose of this synthesis report is to present the expected impacts of a range of mobility policies in the urban transport domain, particularly those relevant to passenger cars, against the background of increasing CAV deployment in the urban vehicle fleet on the environment, mobility, society, safety, and economy.

This report is structured as follows; following this general introduction to the LEVITATE project, *Chapter 2* provides a more detailed theoretical and empirical background to the expected impacts of automated urban transport, and it describes which approach was used to summarise the various impact results from earlier LEVITATE Deliverables D6.2, D6.3 and D6.4 (Haouari, et al., 2021; Sha, et al., 2021; Chaudhry et al., 2021). Chapter 3 presents the main summarised findings of the quantitative analyses which were reported in more detail in deliverables D6.2 to D6.4. In Chapter 4, the strengths and limitations of the LEVITATE approach are discussed and broader policy considerations regarding the potential impacts of CCAMs are reflected upon. In Chapter 5, final conclusions and recommendations are drawn.

2 Background

The transition towards cooperative, connected and automated mobility (CCAM) is expected to contribute to the goals of smart and sustainable cities. In LEVITATE, the impacts of CCAM including automated passenger cars in urban transport on these goals have been studied by adopting various methods on different sub-use cases. This Chapter describes the contributions of automated urban mobility on major policy goals (Section 2.1), how the various impacts are interrelated and contribute to the policy goals (Section 2.2). In Section 2.3, the expected impacts of automated passenger cars are described. The sub-use cases are further described in Section 2.4. The approach taken to summarise the impact results is explained in Section 2.5.

2.1 Urban mobility and transport goals

There is no standard European approach for defining goals and indicators for the further development of smart cities. In WP4 of the LEVITATE project, two existing city transport strategies from Greater Manchester (UK), and Vienna (Austria) have been looked at in more detail, specifically in terms of high-level goals on transport developments (Papazikou et al., 2020). WP4 covers the effects of autonomous vehicle share on the goals set out by policymakers of these cities (Papazikou et al., 2020).

The Greater Manchester Transport Strategy 2040 follows the vision "World class connections that support long-term, sustainable economic growth, and access to opportunity for all". The strategy has seven core principles to be applied across their transport network (City of Manchester, 2017):

1. Integrated – allow individuals to move easily between modes and services
2. Inclusive – provide accessible and affordable transport
3. Healthy – promote walking and cycling for local trips
4. Environmentally responsible – deliver lower emissions, better quality vehicles
5. Reliable – confidence in arrival, departure, and journey times
6. Safe and secure – reduce road accidents especially injuries and deaths
7. Well maintained and resilient – able to withstand unexpected events and weather conditions

Table 2.1 summarizes the Greater Manchester Transport Strategy 2040 goals and a method to measure the impacts. For example, under the policy field, the goal is to improve road safety, this will be measured by the number of injury or fatalities, as well as the perception of personal security by transport mode.

Table 2.1: Overview of goals of the City of Manchester for a viable transport system of the future and corresponding impact targets (City of Manchester, 2017).

Policy field	Policy goal	Measured impact
Environment	Reduced greenhouse gas emissions Best use of existing infrastructure in order to reduce environmental impacts	CO_2 and NO_2 emissions Percentage of new homes having > level 4 accessibility to the public transport network
Mobility	More reliable journey times Reduced congestion Increase use of sustainable transport (reduce negative impact car use)	departure/arrival time reliability by mode of transport Journey duration by mode Modal split of sustainable transport Share of non-sustainable transport modes
Safety	Improved safety and personal security	Number of killed and seriously injured Perception of personal security by transport mode
Society	Greater health Better access to services	Number of walking and cycling trips Sustainable transport catchment population for key locations – town centres/hospitals

The second relevant transport strategy is The Viennese Urban Mobility Plan, under the "STEP 2025 Urban Development Plan". It includes the following goals (City of Vienna, 2015):

1. Fair – street space is allocated fairly to a variety of users and sustainable mobility must remain affordable for all.
2. Healthy – the share of active mobility in every-day life increases; accident-related personal injuries decline.
3. Compact – distances covered between work, home, errands and leisure activities are as short as possible.
4. Eco-Friendly – mobility causes as little pollution as possible, the share of eco-mobility in the trips made in Vienna and its environs is rising. The relative change in the modal shift will be largest in bicycle traffic. In absolute figures, the largest increase in the number of trips will be attributable to public transport.
5. Robust – mobility is as reliable and crisis-proof as possible. Mobility should be possible without necessarily owning a means of transport.
6. Efficient – resources are used in a more efficient way, helped by innovative technologies and processes.

The goals for Vienna span four policy domains and were subdivided into specific policy goals for each domain (*Table 2.2*), each with its own impact measure.

Table 2.2: Overview of goals of the City of Vienna for a viable transport system of the future and corresponding impact targets (WP4).

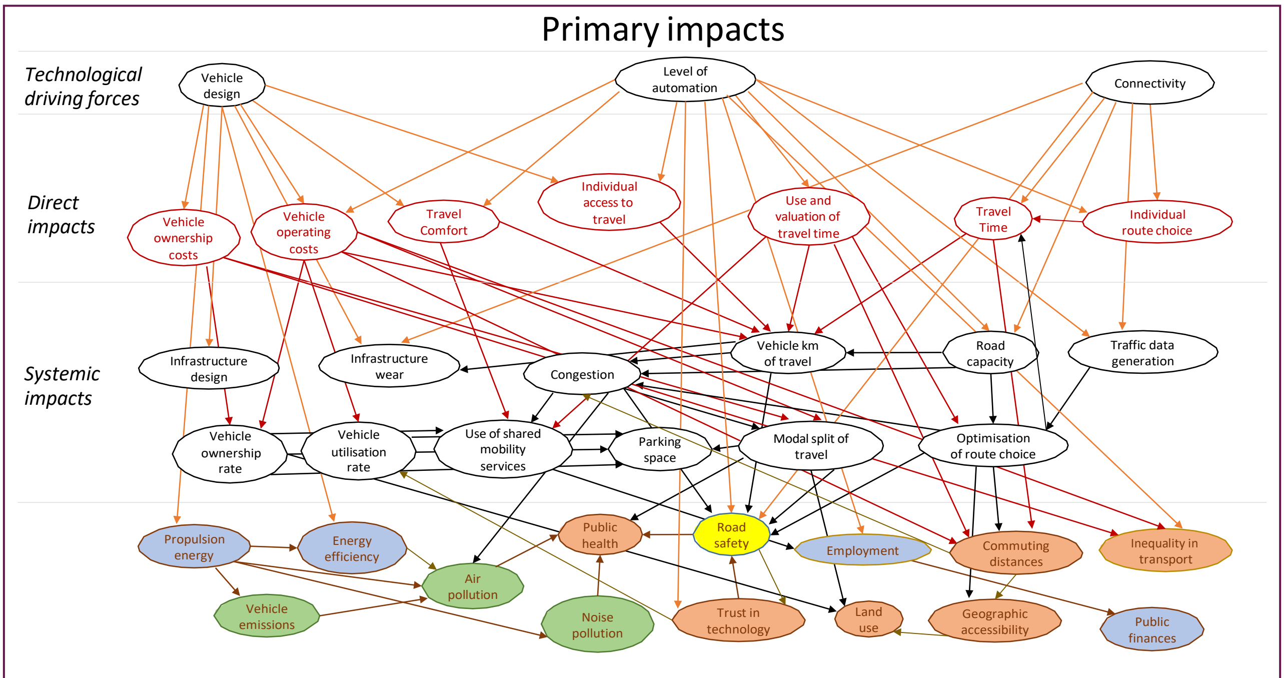
Policy field	Policy goal	Measured impact
Environment	Mobility causes as little pollution as possible	Modal split changes
Mobility	Resources are used in a more efficient way	Absolute final energy consumption of the Vienna transport system
	Distances covered between work, home, errands and leisure activities are as short as possible	The share of trips done on foot or by bike to shop for supplies or accompany someone as well as distances covered for leisure time activities
	Mobility is reliable and crisis-proof	Bicycle availability
Safety	Safe road travel	The number of traffic casualties and persons injured in traffic accidents
Society	Better health: The share of active mobility in every-day life increases	The share of people in the Viennese population who are actively in motion for 30 minutes daily as they run their daily errands
	Fairness: Street space is allocated fairly to a variety of users and sustainable mobility must remain affordable for all	The total sum of spaces for cycling, walking and public transport in all conversion and urban renewal projects

These two city transport strategies reveal that CCAM could contribute toward achieving these goals although specific policy will need to be adopted to make that achievable. For each of the Policy domains described above, one or more key impact indicators have been defined/operationalized for the Policy Support Tool that is intended to help policy makers' decision-making concerning interventions that may support automated driving.

2.2 Expected impacts automation

It is expected that CCAM will have substantial impacts on road transport. Deliverable 3.1 (Elvik et al., 2019) presented a taxonomy of potential impacts of CCAM/CATS which makes a distinction between direct, systemic, and wider impacts. **Direct impacts** are changes that are experienced by each road user on each trip. **Systemic impacts** are system-wide impacts within the transport system and **wider impacts** are changes that occur outside the transport system, such as changes in land use and employment. Moreover, a distinction is made between **primary impacts** and **secondary impacts**. Primary impacts are intended impacts that directly result from the automation technology, whereas secondary impacts (rebound impacts) are generated by a primary impact.

Figure 2.1 presents the various impacts of the taxonomy and their expected interrelations (based on scientific literature and expert consultation). In the figure, impacts are ordered from those that are direct, shown at the top, to those that are more indirect or wider, shown further down in the diagram. The diagram is inspired by the detailed model of Hibberd et al. (2018).



Wider impacts on Environment (green), Economy (blue), Safety (yellow), and Society (orange)

Figure 2.1: Taxonomy of impacts generated by transition to connected and automated vehicles

Figure 2.1 shows the different paths by which impacts are generated by automation technology. Three automation technology aspects are identified: vehicle design, level of automation (SAE 1 to 5), and connectivity (Elvik et al., 2019). These characteristics of technology can give rise to different impacts. For example, vehicle design - which includes aspects such as vehicle size, setup of electronic control units, powertrain (fossil fuel or electric) and ease of getting in or out the vehicle – will, through the technology built into connected and automated vehicles, influence both vehicle ownership cost and vehicle operating cost (Elvik et al., 2019). The choice of powertrain will influence propulsion energy and energy efficiency of the engine. Vehicle design may also influence infrastructure design and infrastructure wear, depending on, for example, the mass of the vehicle and the ability for vehicle to infrastructure communication (Elvik et al., 2019). Finally, vehicle design may influence travel comfort and individual access to transport. As an example, vehicles with high ground clearance and no ramps will be difficult to access for wheelchair users.

Another example of pathways in *Figure 2.1* concerns the primary impacts of CCAMS on road safety. Road safety is influenced by level of automation, as human operator errors will be eliminated at the highest level of automation (there may still be software errors in computer programmes operating the vehicle, but there will be no driver who can make mistakes) (Elvik et al., 2019). The level of automation may also influence road safety indirectly (e.g. through trust in technology), before the highest level of automation is attained. However, even fully automated vehicles will have to interact with non-automated road users, who may place excessive trust in the capabilities of the technology to detect them, brake or make evasive manoeuvres. Connectivity will influence safety by reducing or eliminating speed variation between vehicles travelling in the same direction and by shortening reaction times in case of braking (Elvik et al., 2019). Finally, road safety and, in turn, public health (as related to transport) will be influenced by potential changes in the level of congestion, vehicle kilometres of travel, changes in the modal split of travel and optimisation of route choice (Elvik et al., 2019).

2.3 Expected impacts of automated passenger cars

Literature related to the effects of connected and automated passenger cars on the road transport system is increasingly available. The literature can be divided into five main policy areas covered by LEVITATE (see *Table 1.2* and *Table 1.3*), namely mobility, safety, economy, environment and society. The following paragraphs summarize the literature related to the impacts in each policy domain and based on the findings of the detailed literature review and stakeholder workshop as described in D6.1 (Boghani et al., 2019).

2.3.1 Mobility impacts

Adaptive Cruise Control (ACC) is expected to influence the capacity of roads. The amount and direction of this change is not evident from the current research. Advanced ACC systems might allow for smaller headways, increasing traffic flow according to simulations (Chira-Chavala & Yoo, 1994). However, when headway preferences higher than 1 second are maintained during field tests or simulations, a decrease in capacity occurs (Alkim et al., 2007; Chira-Chavala & Yoo, 1994; Morskink et al., 2007). **In general, ACC has been shown to improve mobility.**

Simulation studies with intelligent speed assist **(ISA)** systems found that ISA leads to slight increases (2,5% on average) in travel time (Carsten & Tate, 2000; Morskink et al., 2007; Vaa et al., 2014). An increase in travel time of up to 5.6% is estimated for strict adherence to speed limits (Vaa et al., 2014). Field trials show no significant increase in travel time for urban areas (Biding & Lind, 2002). **In general, ISA can negatively impact mobility.**

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. However, during the first years of AV implementation the interaction between humans and AVs which could prove to be problematic. Several simulation studies have been carried out to evaluate the impact of providing dedicated lanes for CAVs. These studies found that when the proportion of CAVs is much lower or higher than the proportion of normal cars, then dedicated-AV lanes do not show great impact on capacity. In addition, when the percentage of CAVs are 10-40% of all traffic, then only one dedicated lane provides optimal capacity. Whereas when the percentage of CAVs are 50-90%, then two dedicated lanes provide optimal capacity (Ma & Wang, 2019).

Mohajerpoor & Ramezani (2019) found that the best lane-allocation policy on a two-lane road was found to be:

- One lane for mixed (AV and non-AV), and one lane only for non-AV is ideal for when penetration rate is between 0% and 50%
- One dedicated AV-lane and one dedicated non-AV-lane is ideal for when penetration rate is between 50% and 65%
- One mixed (AV and non-AV), and one dedicated AV-lane is the best policy for when penetration rate is more than 65%

Van der Laan & Sadabadi (2017) conducted a similar study. The impact of introducing an AV-only lane was assessed at various AV-penetration rates, with Vehicle Hours Travelled (VHT), Vehicle Miles Travelled (VMT), average speed and vehicle throughput all plotted against AV penetration rate. The results showed that as penetration rates increased to 30, 40 or 50%, the overall corridor performance (VHT, VMT, speed, throughput) improved the most when there was one fixed AV-only lane, at higher penetration rates the performance started to diminish considerably.

Ye & Yamamoto (2018) used penetration rates, densities, dedicated lane numbers and time in a simulation study and found that establishing CAV dedicated lanes degrades the performance of the total traffic flow at a low CAV penetration rate, particularly at a low traffic density (number of vehicles per kilometre) level. When CAVs become a significant part of the total traffic (higher penetration rate), the benefits of providing dedicated lanes diminish as well. The benefit of establishing a dedicated CAV lane appears most feasible within a moderate traffic density range. The performance of the CAV dedicated lane can be improved by requiring CAVs to go at a faster speed than conventional vehicles on other conventional lanes. Flow-density relationships were also looked at for 0, 1 and 2 CAV lanes, with varying CAV penetration rates from 10% to 90%. **A summary of the studies (presented above) on implementing a dedicated lane for AVs identified that penetration rates of between 30-60% could lead to the best outcomes for traffic speed, speed variances, travel time and traffic density.**

In general, **on-street parking** has a high association with traffic congestion. According to Biswas et al. (2017), on-street parking normally reduces the road capacity in two ways: firstly, on-street parking narrows the carriageway width at the expense of a potential travelled lane affecting both flow and speed. Secondly, frequent parking manoeuvres create congestion on the roads. Together this can result in up to 90% capacity loss (Biswas et al., 2017). A study from Fadairo et al. (2013) indicated that nearly 14% of all congestion on the urban road were caused by on-street parking or parking manoeuvring vehicles. Guo et al. (2012) observed that traffic flow decreased when the proportion of parking manoeuvres was increased.

There are a number of studies that investigated the relationship between on-street parking and traffic delay. Nahry et al. (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 parking turnover had a significant impact on traffic delay. In other words, the higher the volume and the parking turnover, the higher the delay. A similar finding was reported by Borovskoy & Yakovleva (2017). The authors developed a dynamic simulation model that integrated Aimsun software with a Vehicle Tracking application for AutoCAD to study parking turnover impact on traffic delay. The results revealed that the increase in on-street parking turnover leads to an increase in traffic delays. Sugiarto & Limanoond (2013) simulated the impact of on-street parking manoeuvres on travel speed and capacity, using the urban arterial road network of 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 studies also indicated that the reduction in speeds of the traffic stream on urban roads was an immediate consequence of parked vehicles (Biswas et al., 2017). A study conducted by Praburam & Koorey (2015) also 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 demand. A study by Chai et al. (2020) showed that the shift from parking trips to drop-off and pick-up trips improves traffic flow due to reduced parking search time and more efficient use of parking spaces. **In general, on-street parking can have a negative impact on mobility.**

Another study also showed that the parking price could affect the travel time (Qian & Rajagopal, 2014). 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. Several other studies also proved similar results to decrease the travel time with the increasing MPR of CAVs. However, these studies were done for varying parking price conditions. The results may be different when multiple parking choices are available to the passengers. Present study examines different choices of parking to analyse the travel time and delays of vehicles.

2.3.2 Safety impacts

Safety studies of CAVs utilize historic crash data (Farmer, 2008), simulation evaluation data (Kusano & Gabler, 2012), or Field Operational Trial data (Rakha, Hankey, Patterson, & Van Aerde, 2001) to compare the expected and actual impacts of CAVs to a base scenario (Fildes et al., 2015). The following subsections adopt one of the mentioned methods to evaluate the safety impacts of different systems.

Lane Change Assist (LCA) influences possible lane changing crashes. These crashes account for around 5% of all reported crashes (Hynd et al., 2015). The LCA system was expected to prevent 25% of relevant crashes, 9% of relevant fatal crashes and 11% of injuries per year (Farmer, 2008; Jermakian, 2011). The overall actual effects on crash involvements shows a reduction of 14% in relevant crashes and 23% reduction in relevant crashes with injuries (Highway Loss Data Institute, 2019). These results indicate that the implementation of **LCA systems improves safety.**

Lane Departure Warning (LDW) and **Lane Keep Assist (LKA)** systems influence unintended lane departure crashes. In a simulation study, LDW (passive warning), showed a reduction in injury crashes of 6% and fatal crashes of 10% (Hummel et al., 2011). LKA, which is an active method of crash prevention, showed a higher improvement, with a reduction of 5% of injury and 19% of fatal crashes (Jermakian, 2011). Another study evaluated LDW which resulted in reduced relevant injury crashes by 21% (Highway Loss Data Institute, 2019), and LKA reduced injury crashes by 30% (Sternlund 2017). However, other studies considering all crashes show no significant improvement for both LDW (Moore & Zuby, 2013) and LKA (Highway Loss Data Institute, 2012). In general, studies have shown that **LDW and LKA systems can improve safety.**

In-vehicle curve speed warning systems influence crashes that happen due to unsafe speeds in curves. These crashes make up around 4% of all crashes but close to 30% of all fatal crashes (Davis 2018). Studies on expected safety impacts of curve speed warning systems were not found. Actual effects of a curve speed warning system show a decrease of speed by 10% on rural curves on a test track (Davis et al., 2018). A warning system shows similar results to traditional transverse bars on the road, decreasing speed by 6km/h, while a speed limiter shows a decrease of 10km/h in a driving simulator (Comte & Jamson, 2000). Actual safety impacts gathered from a limited number of studies indicate **that curve speed warning systems can improve safety**.

Forward Collision Warning (FCW) and **Autonomous Emergency Braking (AEB)** systems influence rear-end crashes, accounting for close to 30% of all crashes (Jermakian, 2011). In a simulation study, FCW was shown to have a reduction in rear-end collisions between 3% and 67 % (Kusano & Gabler, 2012; Kusano & Gabler, 2015). Studies into the effects of FCW deployments showed an average reduction of 33% in rear end collisions (Cicchino, 2017). The effects of AEB show an average 41% reduction in rear-end crashes (Cicchino, 2017; Fildes et al., 2015). A combination of FCW and AEB showed an overall reduction of 50% in rear-end injuries (Cicchino, 2017) and 23% reduction of all injury crashes (Moore & Zuby, 2013). In summary, implementation of **FCW and AEB systems improves safety**.

Adaptive Cruise Control (ACC) influences crashes related to vehicle headway and speed. Initial studies and trials with ACC estimated that all injury crashes could be reduced by 3% and 13% (Alkim et al., 2007; Chira-Chavala & Yoo, 1994; Vaa 2014). However, to date the effects of wider deployment of ACC remain unclear. ACC can result in both higher and lower mean speed (Morskink et al., 2007), and shows no significant impact on crashes (Rakha et al., 2001). Based on these studies, the **effects of ACC systems on safety have not been established**.

Intelligent Speed Assist (ISA) impacts on crashes related to speed. ISA was expected to reduce overall crashes with injuries between 6 and 27% (AVV, 2001; Regan et al., 2006). Actual effects on number of crashes are not known. ISA is reported to reduce average speed by 2-7km/h (AVV, 2001; Morskink et al., 2007), which is expected to result in a reduction of crashes. Studies in the UK, France and Australia have estimated strong positive effects of compulsory ISA on the number of fatalities and serious injuries. Based on these studies SWOV assumes crash reductions of 30% for fatal crashes and 25 for serious injury crashes (SWOV, 2021). Therefore, the **effects of ISA systems on safety are expected to be positive, particularly with respect to compulsory systems which reduce speeds and reduce the number of fatalities and serious injuries.**

Bike and Pedestrian Detection systems can influence crash rates with pedestrians and cyclists, accounting for around 1% of all crashes but more than 10% of fatal crashes (Yanagisawa 2014). These systems reduced relevant injury crashes by between 4% and 24% for pedestrians and by 44% for cyclists (Hummel et al., 2011; Van der Zweep et al., 2014). Another study showed a reduction of 35% in injury for pedestrians on a test-track (Yanagisawa et al., 2014). No relevant data for cyclist crash reduction was found. The **research on this topic is still limited.**

Intersection Movement Assist (IMA) and **Turn Assist (TA)** systems influence crossing path crash rates on intersections and crossings, covering around 26% of all crashes (Pierowicz et al., 2000). The systems were expected to reduce relevant crashes between 0% and 64% with warning only (Pierowicz et al., 2000; Scanlon, 2017), and 25% to 59% when combined with AEB systems (Scanlon et al., 2017). More recent studies field trials revealed reductions of between 0% to 26% in all crossing path crashes at intersections (Wu et al., 2018). This range is dependent on the TTC. No reduction is found for TTC below 3 seconds, while 26% reduction is found for a TTC of 5 seconds. The studies on this system are **insufficient to draw a conclusion**.

Other Studies

On-street parking has been found to cause hazards and increases the risk to vulnerable road users (Prakash et al., 2020; Biswas et al., 2017). In a complex urban environment, drivers must monitor traffic movements in the immediate and surrounding environment i.e., vehicles, pedestrians and other road users. Parked vehicles can increase the uncertainty, mental load and potential risk associated with the road environment. Parked cars may obstruct the view of the road ahead and make it more difficult to see pedestrians crossing the road (Eddquis et al., 2012). There is a number of studies that found that child injury on urban roads might have a strong relationship with on-street parking (Martin, 2006; Schwebel, 2012; DiMaggio & Durkin, 2002) because of children's limited ability to able to judge an oncoming vehicle given the decreased visibility due to parked cars (Biswas et al., 2017).

2.3.3 Economic impacts

With the many different types of ADAS considered in the literature, no clear cost implications can be extracted for the purpose of this report. However, it is clear that vehicles equipped with these systems are more expensive to produce and to buy. The installation, maintenance, and possible repair costs of ADAS equipped vehicles are higher than comparable vehicles without these systems. The reduction in crashes due to these systems result in lower long-term costs, ultimately benefitting both individuals and society. No direct studies have been found in the literature regarding pricing, and safety implications for the economy.

Regarding fuel consumption, field tests give insight on the impacts of **ACC** and **ISA**, with ACCs reducing fuel consumption, due to lower speed deviations and smoother traffic flow, by 3% overall (Alkim et al., 2007; Kessler et al., 2012). These results match those found in earlier simulations (Bose & Ioannou, 2003). ISA also shows a reduction in fuel consumption of 1,5% on motorways and 5% on urban roads (Kessler et al., 2012). However, another study (Regan et al., 2006) found no significant change during similar tests.

It is generally supported that the implementation of road-user pricing systems (specifically cordon schemes of congestion pricing) in large urban areas could have a beneficial and wider impact on society (IEA/OECD, 2015). *Table 2.3* summarises the characteristics of road-charging schemes in four cities.

Table 2.3 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

Road user pricing (RUP) policies such as these appear to decrease congestion by reducing traffic demand (and thereby volumes) and vehicle travel. Other beneficial impacts include reduced emissions, CO_2 emissions reductions and improved road safety (Transport for London, 2007; Eliasson et al., 2009).

Liu et al. (2020) analysed the impact of pricing on public parking spaces. The author concluded that increasing the parking price would increase the government revenue from parking and buses. Further, the parking prices would discourage motorists from using personal vehicles and promoting public transport. The maximum benefit of this scheme could be obtained with optimal parking prices.

2.3.4 Environmental impacts

Reductions in fuel consumption translate into reductions in emissions. Further effects on emissions are found in field tests and simulations with **ACC** which found 10% reduction in emissions on motorways (Alkim et al., 2007; Bose & Ioannou, 2003). This was mainly due to changes in speed variations. However, an increase of the average speed with ACC increases regular emissions by 1-2% (Kessler et al., 2012). **ISA**, on the other hand can lead to lower average speeds in turn leading to significant reductions in emissions (Kessler et al., 2012; Regan et al., 2006). Combining ACC with ISA is considered beneficial since it allows for a decrease in speed variations due to ACC, without the accompanying increase in average speed by limiting maximum speed with ISA.

As mentioned above, the implementation of road-use pricing systems can lead to reduced CO_2 emissions (Transport for London, 2007; Eliasson et al., 2009).

A study by Chai et al. (2020) indicated that too many drop-off and pick-up spaces instead of parking spaces could increase CO_2 emissions from vehicles that got stuck in traffic congestion. They suggested that converting parking spaces to drop-off and pick-up spaces should be street specific and dynamic over-time.

2.3.5 Societal impacts

Because many of the current CAV systems are optional and not widely implemented, no discernible impacts on society were found in the literature. Many of the systems reduce driver stress during vehicle operation, potentially allowing more individuals to drive. This effect might be strongest for older drivers, allowing them more mobility. This is particularly relevant for the systems involved with backing up and parking assistance, such as rear-view cameras. Questionnaires on these systems show a higher willingness to use parking spaces and prevent avoidance of backing up (Jenness et al., 2007).

Results from ISA field trials show that while the system is accepted by the driver of the vehicle, other drivers become more irritated (AVV, 2001). This is a result of the strict adherence to speed limits, which forces other drivers to either adjust their speed accordingly or overtake the equipped car. On average 2 out of 3 drivers experienced negative interactions with other drivers, of which 17% were aggressive interactions (AVV, 2001). These interactions with irritated drivers were one of the main reasons the ISA system was found disabled by the driver, accounting for 14% of all emergency interruptions of the system (AVV, 2001).

Another study also showed that the parking price could affect the travel time (Qian & Rajagopal, 2014). 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. Several other studies also proved similar results to decrease the travel time with the increasing MPR of CAVs. However, these studies were done for varying parking price conditions. The results may be different when multiple parking choices are available to the passengers. Present study examines different choices of parking to analyse the travel time and delays of vehicles.

On-street parking can significantly impact traffic performance and may create or exacerbate various problems for urban cities. In this respect, a recent study conducted by Haider et al. (2021) revealed the effects of on-street parking in Chittagong City, Bangladesh. The results showed that on-street parking could have the following negative effects: narrows down the road (47%); footpath crisis (29%); noise and air pollution (23%), shops get blocked (5%), and loss of time (30%). 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 et al., 2017; Anderson et al., 2016; Chapin et al., 2016; Fagnant et al., 2015), and creating more space for the high-quality, liveable area (Gonzalez et al., 2020; 2019), especially in the context of shared autonomous vehicles (SAVs) that could reduce the number of the required parking spaces due to the SAVs will be serving customers at different times (Othman, 2021). Consequently, a large number of existing parking spaces will be gradually removed or replaced or converted for other purposes, e.g., green and recreational spaces (Xia et al., 2021; Milakis et al., 2017; Chapin et al., 2016).

2.4 Sub-use cases

Findings from the stakeholders' reference group (SRG) meeting and recent literature suggest that certain pricing policies and regulations (e.g., road use pricing, parking fee, dedicated lanes, the cost of owning and operating a car, etc.) can directly influence the impacts of increasing automation. Within Work Package 6 of LEVITATE, the following six policies and technologies are selected for further analysis in what are called sub-use cases (SUCs):

1. Road-use pricing
2. Provision of dedicated lanes for CAVs on urban highways
3. Parking price regulation
4. Replacing on-street parking
5. Automated ride sharing
6. Green Light Optimal Speed Advisory (GLOSA)

Besides the overall impacts of an increasing number of CAVs on the road, the impacts of automation combined with each of these six measures is quantified within the SUCs. The methods and full results of this quantification are described in full in deliverables D6.2-6.4 (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021). These results are summarised in this synthesis report and Sub-sections 2.4.1-2.4.6 describe each SUC in more detail.

SUC methodologies

The impacts of the SUCs are quantified using four methodologies: microsimulation, mesosimulation, system dynamics (SD) and Delphi. In Appendix A, the methodologies are explained in more detail. Depending on the methodology and sub-use case, impacts are estimated based on four cities—Vienna (Austria), Manchester (UK), Leicester (UK), and Santander (Spain)—or based on one of the expert groups consulted for the Delphi study, which is not location specific. In Appendix C, these networks are described.

Methodologies were applied to different sub-use cases and impacts based on their strengths and capabilities. *Table 2.4* gives an overview of which methodologies were used to estimate the SUC impacts. Microsimulation was well-suited for modelling dynamics in traffic where individual car behaviour is important, such as congestion or road safety. Mesoscopic simulation and SD modelling, on the other hand, were better suited to considering indirect effects and changes in travel behaviour (e.g., a modal shift, amount of travel per person). Because road-use pricing is primarily focused on changing travel behaviour choices, it was not estimated with microsimulation.

For impacts which could not be estimated by any of the three modelling methods, expert opinion was evaluated using a Delphi study. Some impacts were also calculated by both the Delphi study and one of the other methods. For the complete set of Delphi results in Work Package 6, see deliverables 6.2 through 6.4 (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021).

Table 2.4: Methodologies used per sub-use case and per quantified impact in Work Package 6

Policy area	Impact	Sub-use cases: 1.Road user pricing	2.Dedicated CAV lanes	3.Parking price regulation	4.Replacing on-street parking	5.Automated ride sharing	6.GLOSA
Environ-ment	CO_2 emissions due to vehicles		Microsimulation (Manchester)	Microsimulation (Santander)	Microsimulation (Leicester)	Microsimulation (Manchester)	Microsimulation (Manchester)
	Energy efficiency	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
Mobility	Travel time*	Mesosimulation (Vienna)	Microsimulation (Manchester)	Microsimulation (Santander)	Microsimulation (Leicester)	Microsimulation (Manchester)	Microsimulation (Manchester)
	Access to travel	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
	Amount of travel per person*	Mesosimulation (Vienna)					
	Total kilometres travelled		Microsimulation (Manchester)	Microsimulation (Santander)	Microsimulation (Leicester)	Microsimulation (Manchester)	Microsimulation (Manchester)
	Congestion		Microsimulation (Manchester)	Microsimulation (Santander)	Microsimulation (Leicester)	Microsimulation (Manchester)	Microsimulation (Manchester)
	Modal split: Active travel	SD (Vienna), Delphi	Delphi	SD (Vienna), Delphi	SD (Vienna), Delphi	SD (Vienna), Delphi	Delphi
	Modal split: Public transport	SD (Vienna), Delphi	Delphi	SD (Vienna), Delphi	SD (Vienna), Delphi	SD (Vienna), Delphi	Delphi
	Shared mobility rate	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
	Vehicle utilisation rate	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
	Vehicle occupancy	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
Society, safety, economy	Vehicle operating cost	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
	Parking space demand*	SD (Vienna)		SD (Vienna)	SD (Vienna)	SD (Vienna)	
	Road safety		Microsimulation (Manchester)	Microsimulation (Santander)	Microsimulation (Leicester)	Microsimulation (Manchester)	Microsimulation (Manchester)
	Public health	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
	Accessibility of transport	Delphi	Delphi	Delphi	Delphi	Delphi	Delphi
	Average commute distance	SD (Vienna)		SD (Vienna)	SD (Vienna)	SD (Vienna)	

**The Delphi method was also used to estimate a simplified form of these impacts but is excluded from this synthesis report. For Delphi results on travel time see Haouari et al. (2021), for amount of travel see Sha et al. (2021), and for parking space demand see Chaudhry et al. (2021)*

2.4.1 Road-use pricing

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

The road-use pricing SUC is evaluated using *mesosimulation* and *system dynamics*, both on the street network of **Vienna** (Austria), as well as the *Delphi* expert survey. In the *mesosimulation,* the static toll is considered as a fixed fee to enter the city centre of Vienna at a price of €5, €10 or €100. The dynamic toll is implemented as a fee per kilometre travelled within the city centre, again with three pricing levels. The per kilometre tolls are set such that a trip to cross the entire city centre of Vienna (roughly 7 kilometres) would again be equal to €5, €10 or €100. This results in dynamic tolls of €0,71 per km, €1,43 per km or €14,29 per km. *System dynamics* considers just a static toll with a level of €10 for the city centre of Vienna, while the *Delphi* study considers three scenarios—empty kilometre pricing, static toll, and dynamic toll—in a more abstract form not specific to a certain price or location.

2.4.2 Provision of dedicated lanes for CAVs on urban highways

According to the Connected Automated Driving Roadmap from ERTRAC (2019), a dedicated AV Lane is a lane which only allows vehicle(s) with specific automation level(s). Automated vehicles are, however, not physically confined to the dedicated lane, which would instead be referred to as a physically separated lane. It is envisaged that where a dedicated public transport lane is in operation, the dedicated AV lane would be shared with the dedicated public transport lane, allowing both types of vehicles (as is the case with current High Occupancy Vehicle (HOV) lanes). Such a dedicated lane may be fixed (dedicated to CAVs at all times), or it may be dynamically controlled to vary based on the traffic situation.

The dedicated CAV lane SUC is evaluated using *microsimulation* in a portion of the **Greater Manchester** (United Kingdom) network, as well as the *Delphi* expert survey. The *microsimulation* considers, for a portion of the network surrounding the centre of Manchester, what the impacts may be of a fixed dedicated lane on an A-level road and/or a motorway in the following scenarios: motorway and A-roads, A-road only rightmost lane, A-road only leftmost lane, and motorway only. The *Delphi* method considers four scenarios of a fixed dedicated lane (Outermost motorway lane, Innermost motorway lane, Outermost motorway lane & A-road), as well as a dynamically controlled CAV dedicated lane.

2.4.3 Parking price regulation

In the Stakeholder group (SRG) meetings, parking and related issues were identified as an additional subject warranting its own use case or sub-use case. The opinion of stakeholders was that for CAVs to be successfully implemented, challenges related to parking (location, space availability, pricing, etc.) would require attention. Unlike human-driven vehicles, which are typically parked at or near the destination (if not transferring to another mode of transportation), full automation could allow vehicles to park at a different location after dropping off passengers at the destination. This parking price sub-use case investigates the potential impacts of discouraging inner-city parking by increasing the fees to park within a certain area. It is assumed that as a result of changes in parking fees, some automated vehicles may either drive around while waiting for passengers or park at a cheaper location outside the area.

The parking price regulation SUC is evaluated using *microsimulation* in the network of **Santander** (Spain), *system dynamics* modelling based on the city of **Vienna** (Austria), and the *Delphi* expert survey. Rather than implementing an actual increased parking fee, the effects of which on choice behaviour are outside of the scope of microsimulation, the *microsimulation* considered the effects of resulting changes in parking behaviour. Four possible parking behaviours were identified, shown in *Figure 2.2*, where the "area" is defined as the city centre which would have a higher cost of parking:

Figure 2.2: CAVs Simulated parking behaviours resulting from parking price regulation

From these four parking behaviour options, the *microsimulation* simulated four scenarios using the network of Santander:

1. Baseline scenario: increasing penetration of automated vehicles without a policy intervention to change parking behaviour (cars park within central area)
2. Drive-around scenario: all cars drive around without parking until the passenger is ready to be picked up
3. Balanced scenario: cars park either inside centre (13%), return to origin (22%), drive outside centre to park (45%), or drive around until passenger is ready (20%)
4. Return to origin and Park outside: cars either return to origin (33%) or drive outside centre to park (67%)

The *system dynamics* model, which is able to explicitly consider choice behaviour and indirect effects such as a mode shift, implemented the same "balanced scenario" for automated vehicle parking behaviour with the additional inclusion of a 5 euro average parking fee. The *Delphi* study evaluated the expected effects of each of the four behaviours described in *Figure 2.2* separately in the following scenarios: baseline, park inside, return to origin, drive around and park outside.

2.4.4 Replacing on-street parking

On-street parking is the most common parking provision provided for all paid and unpaid parking activities along roadsides in urban cities (Biswas et al., 2017). It allows drivers to park their vehicles relatively close to their destinations and share the available road space with other vehicles moving on the street (Prakash et al., 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 crashes. Theoretically, the introduction of autonomous vehicles offers the potential to reduce the urban space requirements for roads and parking, as automated vehicles are able to park elsewhere after dropping passengers off at the destination (as discussed in the previous SUC on parking price regulation). This opens up new opportunities to create more space for high-quality and liveable areas (Gonzalez et al., 2020; Gonzalez et al., 2019). In LEVITATE WP6, we assess the impacts of replacing on-street parking with other facilities given the autonomous development of CAVs.

The replacing on-street parking SUC is evaluated using *microsimulation* in the city centre network of **Leicester** (United Kingdom), *system dynamics* modelling based on the city of **Vienna** (Austria), and the *Delphi* expert survey. The *microsimulation* considers the following six scenarios for removing on-street parking facilities:

1. Baseline scenario: increasing CAV penetration without replacing on-street parking. Includes a total of 52 streets with 138 parking bays for 4 parking zones (see *Figure 2.3a*).
2. Removing half of the on-street parking spaces: the on-street parking spaces for 4 parking zones were reduced by 50%, resulting in 28 streets with 79 parking bays.
3. Replacing on-street parking spaces with driving lanes: on-street parking spaces are converted to driving lanes (shown in *Figure 2.3b*).
4. Replacing on-street parking spaces with cycling lanes: on-street parking spaces are converted to a dedicated cycle lane (shown in *Figure 2.3c*), which means other vehicle types are not allowed to use the cycle lane. It should be noted that the bicycle traffic could not be explicitly simulated due to software limitations.
5. Replacing on-street parking spaces with pick-up and/or drop-off points (see *Figure 2.3d*): The scenario assumes the CAVs are shared CAVs. As a result, after the vehicle picks up or drops off the passenger, the vehicle will exit the study area to return home or to serve another customer.
6. Replacing on-street parking spaces with public spaces. In this scenario, on-street parking spaces were converted to public spaces, e.g., green, and recreational spaces (shown in *Figure 2.3e*).

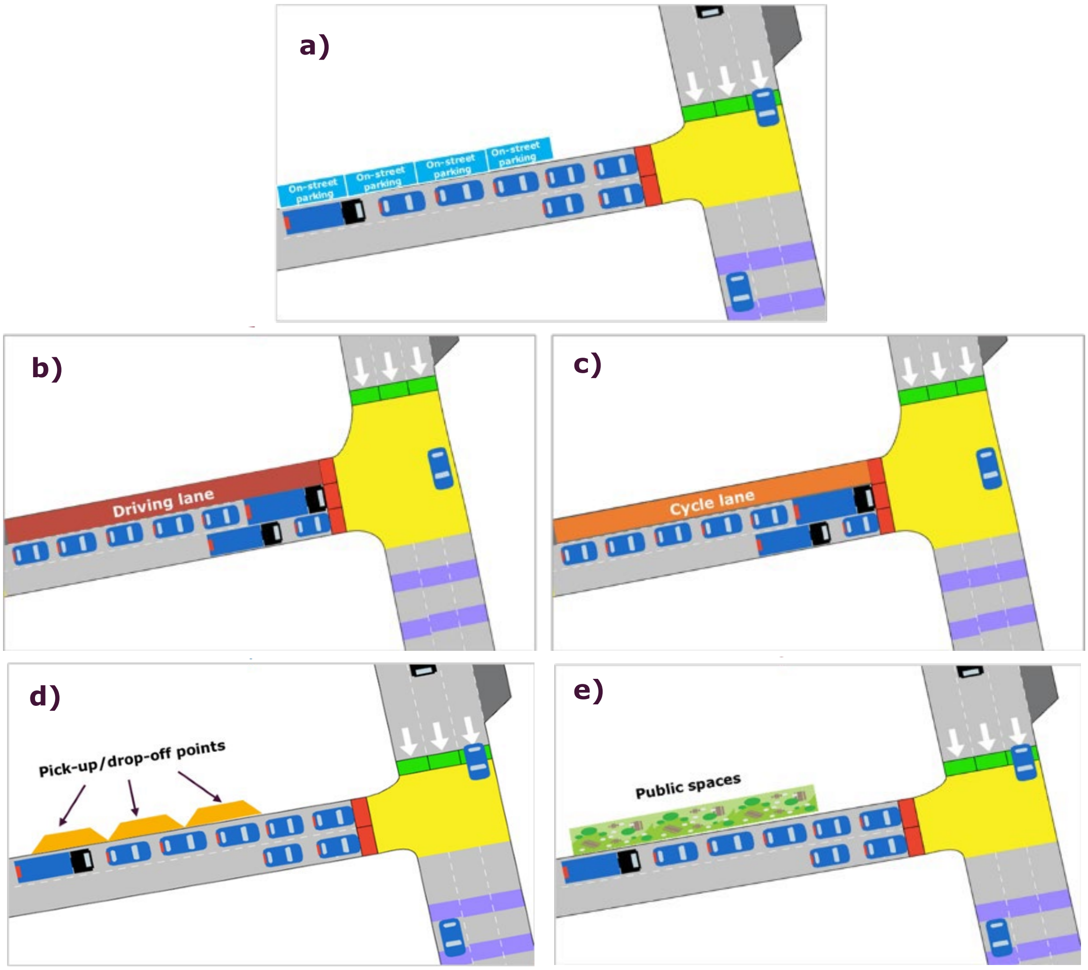


Figure 2.3: Replacing on-street parking with driving lane, cycle lane, pick-up/drop-off points, or public spaces

For *system dynamics*, only the first three scenarios were considered: baseline, removing half of on-street parking spaces, and replacing on-street parking with driving lanes. Unlike microsimulation, which focuses on the more direct effects on traffic, system dynamics also considered the effects of parking availability on mode choice (longer parking search times increase the "costs" of choosing to use a private car).

2.4.5 Automated ride sharing

Conventional ride sharing is a model where the private car is shared via pre-arranged journeys. Ride sharing is pre-arranged within, for example, neighbourhoods, community, the workplace, informally via ride-matching web and apps. In terms of CCAM, this is seen as having a minor role as there is not much change in its operation.

Sharing taxis has been done informally at taxi stands by identifying passengers sharing 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 other passengers if they wish to share. Matched ride options are also available to users via apps and these are handled by optimising algorithms. CCAM will play a significant role in this model as connectivity will enhance the taxi sharing options, and automated vehicles are speculated to reduce taxi costs.

Micro-transit services or-demand mini-bus services are services operating along fixed or flexible routes and based on demand. These are usually commercial services, and the number of seats is usually greater than those of taxis. This option overlaps with the urban shuttle sub-use case in LEVITATE's Work Package 5 and does not seem to be a passenger car sub-use case so is not further considered.

Out of these options, it has been recognised that automated taxi ride sharing is the fastest emerging business and is already in operation in many cities worldwide. Given the above arguments regarding the suitability of these use cases, only the automated taxi ride sharing has been taken forward as a preferred sub-use case to investigate within this work package.

The automated ride sharing SUC is evaluated using *microsimulation* on a portion of the **Greater Manchester** (United Kingdom) network, *system dynamics* modelling based on the city of **Vienna** (Austria), and the *Delphi* expert survey.

The *microsimulation* of automated ride sharing considers many scenarios but varying two parameters: the percentage of total private vehicle trips replaced by automated ride sharing (5%, 10%, or 20%), as well as the willingness of ride sharing passengers to share their trip with other travellers (20%, 50%, 80% or 100%). Automated ride sharing vehicles are assumed to be a fully autonomous, on-demand service which picks passengers up at their origin and drops them off at their destination and, if possible, combines this trip with another passenger's trip. Trips are only shared when all passengers are willing to share trips (randomly assigned based on the willingness to share scenarios) and each passenger's acceptable detour time (normally distributed between 5 and 10 minutes) is not exceeded. The fleet sizes of ride-sharing vehicles are optimised based on travel demand and willingness to share.

Regarding travelled distance, *Figure 2.4* shows that a higher willingness to share scenario 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.

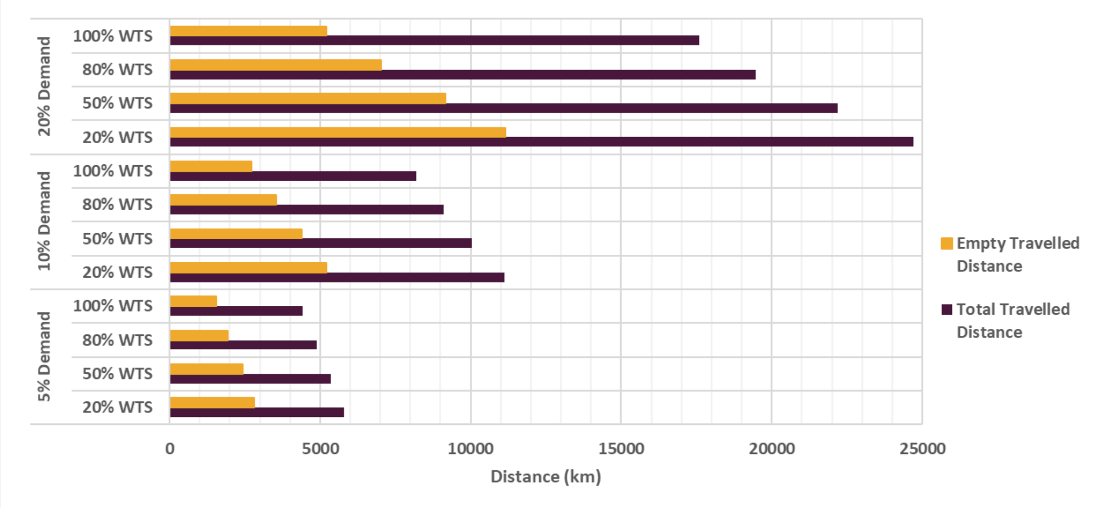


Figure 2.4: Total distance travelled by the shared autonomous vehicle (SAV) fleet in kilometres with different served demand and passengers willingness to share (WTS) percentages

The other two methods used to analyse automated ride sharing considered just one scenario each. *System dynamics* considered automated ride sharing serving 20% of the travel demand with 100% willingness to share, while the *Delphi* survey considered one more general automated ride sharing service scenario without specified parameters.

2.4.6 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 in the short term (Mellegård & Reichenberg, 2020).

Green Light Optimal Speed Advisory (GLOSA) is a traffic signal application at signalised intersections. The application utilises traffic signal information and the current position of a 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. The GLOSA service is provided into the on-board computer of the vehicle or via mobile network to a smartphone app.

In recent years, technological achievements have made wireless communications with and between vehicles possible. Connected vehicle technology includes vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) and communication has several safety and mobility applications (Radivojevic et al., 2016). As traffic information becomes accessible, connected vehicles are able to adapt their movement according to traffic conditions which can contribute to beneficial changes in traffic flow and emissions (Masera et al., 2019). One emerging V2I 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 is schematically illustrated in *Figure 2.5.*

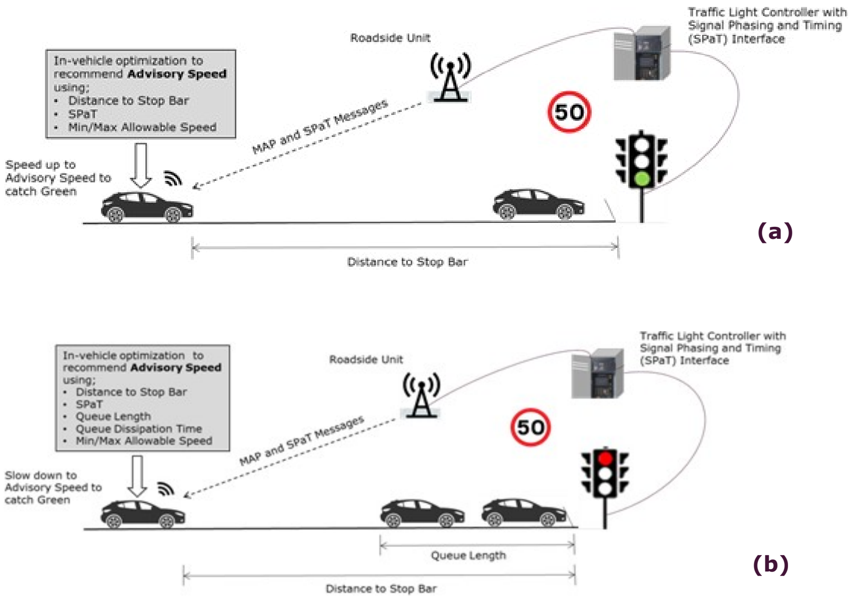


Figure 2.5: GLOSA system and application overview: (a) Communication initiated when current phase is Green, (b) Communication initiated when current phase is Red

In the 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.

The GLOSA SUC is evaluated using *microsimulation* on a portion of the **Greater Manchester** (United Kingdom) network as well as the *Delphi* expert survey. For implementing GLOSA in *microsimulation*, a corridor near the Salford area was selected in Manchester with three signalized intersections sufficiently distant from each other. The impact of GLOSA was analysed for peak-hour traffic conditions, with scenarios considering none (baseline), one, two, or three signalized intersections to be GLOSA-equipped. The *Delphi* survey considered GLOSA more generally, as either present or not (baseline).

2.5 Approach to synthesizing results

The goal of this Deliverable is to summarize the more detailed results presented in D6.2-D6.4 (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021). As has been explained in Section 1.2, the impacts expected from an increasing penetration rate of CAVs in the total vehicle fleet as well as the implementation of different SUCs were studied using four primary methods: microsimulation, mesosimulation, system dynamics, and Delphi consultation. In each method, results were estimated based on either multiple simulation runs or multiple rounds of the Delphi survey, averaged to an expected impact for each penetration scenario. In this synthesis, these impacts are presented in terms of percentage changes from the starting point or baseline scenario (no SUC implemented; 0% automated vehicles).

Given the many uncertainties in prediction for a technology which is not yet widely available, it is obvious that any predicted values are associated with large uncertainty. The impacts calculated within LEVITATE are therefore intended to be understood more broadly as an indication of the expected trends, rather than a precise prediction. For WP6, it was decided not to include all estimates of confidence intervals based on the standard error, derived from repeated trial runs of models in the simulation methods, as a standard output since these intervals would be broad and non-informative. Also, the estimation of these intervals does not capture the entire uncertainty in itself since the input variables and assumptions in the models are very likely much stronger determinants of predicted values than the variability in sample runs. Nevertheless, the standard deviations between simulation runs can give some insight into the random variation in the models and have therefore been calculated for the baseline scenario in the three city-level microsimulation networks: Manchester, Leicester and Santander (see Appendix C).

For each of the six sub-use cases, a number of scenarios were estimated including both a Baseline and different variations of the measure's implementation (see *Table 2.5*). As described in Section 2.4, not all methods were equally well-suited to estimate the impacts of all sub-use cases and scenario's (e.g. road use pricing impacts were best estimated by the larger-scale mesosimulation and system dynamics methods). For the purposes of this synthesis, the results estimated as part of WP6 and described in D6.2, D6.3 and D6.4 (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021) were aggregated and summarised to provide an overall overview. Depending on the sub-use case, this meant excluding some scenarios from the overview which provided similar insights as other scenarios (e.g. lower demand shares of automated ride sharing) or represented less realistic extremes (e.g. all cars not parking and remaining on the roads due to parking price regulation). For some sub-use cases, an average is taken of a few scenarios which consist of small variations of the same intervention and show similar results (e.g. different placements of a dedicated lane for the UK context). An average was chosen to provide a more generalized trend for the SUC less specific to the simulation parameters and because the largely similar results between scenarios suggest an overarching trend regardless of scenario. The full results, broken down per scenario, can be found in Appendix D. In addition, some estimates of the confidence intervals calculated from the microsimulation results (in particular travel time, congestion and total km travelled), are provide in Appendix D.

Table 2.5: Synthesized automated passenger car sub-use case scenarios from Deliverables 6.2-6.4

Method applied to assess impacts	Sub-use case applied to	Scenarios covered by SUC	Synthesized results (impacts estimated as % change)
Micro-simulation *(several city networks)*	Dedicated lanes for CAVs *(Manchester network)*	• Baseline • Motorway and A-roads • A-road rightmost lane • A-road leftmost lane • Motorway only	• **Baseline** • **Dedicated lane (fixed)** *Average: Motorway and A road, A road right most lane, A road left most lane, Motorway only*
	Parking price regulation *(Santander network)*	• Baseline • Drive around without parking • Balanced scenario: cars park either inside city centre (13%), return to origin (22%), drive outside city centre to park (45%), or drive around until passenger is ready (20%) • Return to origin (33%) or park outside city centre (67%)	• **Baseline** • **Adjusted parking behaviour (Balanced scenario)** *Balanced scenario: cars park either inside centre (13%), return to origin (22%), drive outside centre to park (45%), or drive around until passenger is ready (20%)*

Method applied to assess impacts	Sub-use case applied to	Scenarios covered by SUC	Synthesized results (impacts estimated as % change)
	Replacing on-street parking *(Leicester network)*	• Baseline • Removing half on-street parking spaces • Replacing with driving lanes • Replacing with pick-up/drop-off points • Replacing with public spaces • Replacing with cycling lanes	• **Baseline** • **Removing half on-street parking spaces** • **Replacing with driving lanes** • **Replacing with pick-up/drop-off points** • **Replacing with public spaces** • **Replacing with cycling lanes**

	Automated ride sharing
	
	(Manchester network)
		• Baseline
		• 5% travel demand served:
		  ○ 20% willingness to share
		  ○ 50% willingness to share
		  ○ 80% willingness to share
		  ○ 100% willingness to share
		• 10% travel demand served:
		  ○ 20% willingness to share
		  ○ 50% willingness to share
		  ○ 80% willingness to share
		  ○ 100% willingness to share
		• 20% travel demand served:
		  ○ 20% willingness to share
		  ○ 50% willingness to share
		  ○ 80% willingness to share
		  ○ 100% willingness to share
			• **Baseline**
			• **20% travel demand served & 20% willingness to share**
			• **20% travel demand served & 100% willingness to share**

	Green Light Optimised Speed Advisory (GLOSA) *(Manchester network)*	• Baseline • GLOSA on 1 Intersection • GLOSA on 2 Intersections • GLOSA on 3 Intersections	• **Baseline** • **GLOSA on 3 Intersections**

Meso-simulation
 	
(Vienna network)
	Road-use pricing	• Baseline: Zero charge
		• Static toll (to enter city centre):
		  ○ 5 euros
		  ○ 10 euros
		  ○ 100 euros
		• Dynamic toll (€/km in city centre):
		  ○ 5 euros to cross city (€0,7/km)
		  ○ 10 euros to cross city (€1,4/km)
		  ○ 100 euros to cross city (€14/km)
			• **Baseline**
			• **Static toll: 10 euro**
			• **Dynamic toll: 1,4 euro/km**

System dynamics *(Vienna network)*	Road-use pricing	• Baseline • Static toll: 10 euros	• **Baseline** • **Static toll: 10 euros**
	Parking price regulation	• Baseline • Balanced scenario (same as microsimulation) + 5 euro average parking fee	• **Baseline** • **Adjusted parking behaviour** *Balanced scenario (same as microsimulation) + 5 euro average parking fee*

Method applied to assess impacts	Sub-use case applied to	Scenarios covered by SUC	Synthesized results (impacts estimated as % change)
	Replacing on-street parking	• Baseline • Remove half of public parking space • Replace on-street parking with driving lanes	• **Baseline** • **Removing half on-street parking spaces** • **Replacing with driving lanes**
	Automated ride sharing	• Baseline • 20% travel demand served & 100% willingness to share	• **Baseline** • **20% of demand & 100% willing to share**
Delphi study *(expert survey)*	Road use pricing	• Baseline • Empty km pricing • Static toll • Dynamic toll	• **Baseline** • **Empty km pricing** • **Static toll** • **Dynamic toll**
	Dedicated lanes for CAVs	• Baseline • Outermost motorway lane • Innermost motorway lane • Outermost motorway lane & A-road • Dynamically controlled CAV dedicated lane	• **Baseline** • **Dedicated CAV lane (fixed)** *Average: Outermost motorway lane, Innermost motorway lane, Outermost motorway lane & A-road* • **Dedicated CAV lane (dynamic)** *Dynamically controlled AV dedicated lane*
	Parking price regulation	• Baseline • Park inside • Return to origin • Drive around • Park outside	• Baseline • **Adjusted parking behaviour** *Average: Park inside, Return to origin, Drive around, Park outside (comparable with microsimulation balanced scenario)*
	Replacing on-street parking	• Baseline • Space for public use • Driving lanes • Pick-up/drop-off	• **Baseline** • **Space for public use** • **Driving lanes** • **Pick-up/drop-off**
	Automated ride sharing	• Baseline • Automated ridesharing	• **Baseline** • **Automated ridesharing**
	Green Light Optimised Speed Advisory (GLOSA)	• Baseline • GLOSA	• **Baseline** • **GLOSA**

The synthesised results are discussed in Chapter 3 and the way in which these are presented is illustrated in *Table 2.5*. The following approach was adopted to summarize and structure the quantified results for WP6:

- Impacts are presented as a **percentage change** from the *Baseline 100-0-0 scenario*, i.e. where no SUCs have been implemented in the network and all vehicles are human-driven. These percentage changes are reported across increasing market penetration rates of CAVs throughout the entire vehicle fleet in the network, as used throughout LEVITATE. See *Table 2.6.*

- The *Baseline* refers to a "no intervention" scenario which is essentially the expected autonomous development of CAVs from human dependence to human independence (see Section 1.1). In the Baseline scenarios there is no policy intervention SUC added to the network.
- The **impacts of CAVs alone** on network performance can be established by comparing the *Baseline 0-0-100 scenario* (0% human-driven vehicles) to the *Baseline 100-0-0 scenario* (100% human-driven vehicles).
- The specific **effect of a sub-use case** can be determined by comparing the *Baseline* situation at a given penetration rate with the respective SUC results; the difference between the baseline and the SUC is the added effect created by implementing the specific SUC intervention in the simulated network.

Table 2.6 Illustration of how to read overview tables in Chapter 3

		Increasing penetration rates of automated vehicle in traffic							
		100% human-driven vehicles							100% automated vehicles
		1	2	3	4	5	6	7	8
Impact	Baseline – no intervention	0% (reference)	% change	% change	% change	% change	% change	% change	% change
	Intervention	% change	% change	% change	% change	% change	% change	% change	% change

3 Main findings: quantified impacts

This Chapter presents a summary of the impacts that were quantified in the LEVITATE Deliverables 6.2 to 6.4. The findings are presented for all 5 policy domains selected within LEVITATE, namely Environment (Section 3.1), Mobility (Section 3.2), and Society/Safety/Economy (Section 3.3). These sections describe the synthesised results according to each of the applied methods as described in Section 2.5 and *Table 2.4*. More detailed findings from D6.2 to 6.4 including all of the estimated sub-use case scenarios can be found in tables in Appendix D.

3.1 Impacts on the environment

In LEVITATE, four indicators were used to measure impacts on the environment: carbon dioxide (CO_2) emissions, nitrous oxide (NO_x) emissions, particulate (PM_{10}) emissions, and energy efficiency. Their importance for the environment has been widely documented (e.g., EEA, 2020). In this WP6 synthesis report, we describe the environmental impacts using CO_2 emissions and energy efficiency (see *Table 3.1)*. Carbon dioxide emissions are the primary driver of global climate change, and it is widely recognised that in order to decrease the negative impacts on climate change, the world needs to urgently reduce these emissions. Improving the efficiency of urban transport services and technologies that use energy from fossil fuels will help reduce emissions. Detailed information on the other indicators (NOx and particulate emissions) can be found in the underlying study reports (Haouari, et al., 2021; Sha, et al., 2021; Chaudhry et al., 2021). To estimate the effects of the indicators, two methods are used: Microsimulation for the CO_2 effects and the Delphi method for energy efficiency.

Table 3.1: Environmental impact definitions

Impact	Definition	Methodology
CO_2 emissions due to vehicles	*Concentration of CO_2 pollutants as grams per vehicle-kilometre (all road traffic)*	Microscopic simulation
Energy efficiency	*Average rate (over the vehicle fleet) at which propulsion energy is converted to movement (all road traffic)*	Delphi

The following sections summarise the results from the two methods on the environmental effects of the sub-use case scenarios.

3.1.1 Environment: Microsimulation results

Table 3.2 presents the results from each scenario of a sub-use case given different connected and automated vehicles (CAV) penetration rates. Three vehicle types are considered: 1) Human-drive vehicle, 2) 1st generation CAV, and 3) 2nd generation CAV (see Appendix B for behavioural parameters). In general, looking at the results, it is clear that regardless of the sub-use case or its penetration scenario, the increasing CAV penetration rate in the vehicle fleet reduces CO_2 emissions. This reduction is the highest once human driven vehicles no longer are a part of urban traffic (reductions of at least 97% at 0-40-

60; 0-20-80 and 0-0-100 penetration scenarios). An important assumption underpinning these results is that all CAVs introduced into the network are electric vehicles, so non-tailpipe emissions (e.g. due to electricity generation) are outside the scope of this study and therefore excluded. Human-driven vehicles in the network are assumed to use combustion engines powered by fossil fuels. The reductions are thus largely driven by the increasing penetration rates of 1st and 2nd generation (electric) CAVs. Differences between the proportion of CAVs in the network and the reduction in total CO_2 emissions are related to two factors: a small number of non-electric public transport vehicles (share depends on the network considered), as well as variations in the traffic situation (e.g. congestion) which affect the vehicle kilometres travelled within a simulation run. Indirect effects, such as a modal shift or change in travel demand, are outside the scope of microsimulation and therefore not reflected in these results.

The results are estimated for all motor vehicle road transport within the network across different CAV penetration rates, with and without policy interventions in networks from three European cities: Manchester, Santander and Leicester. Readers are reminded that differences in the baseline impacts (with no CAV or intervention) reflect differences in the underlying road networks and varying traffic conditions modelled in the simulations of these cities.

Table 3.2 Estimated impacts of CAVs on CO2 emissions using the microsimulation method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs (100-0-0).

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (Human-driven vehicle – 1st Generation CAV – 2nd Generation CAV)								
			100-0-0	**80-20-0**	**60-40-0**	**40-40-20**	**20-40-40**	**0-40-60**	**0-20-80**	**0-0-100**	
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%	%	%	**City**
CO_2 emissions	Dedicated lanes for CAVs	Baseline	0,0	-20,2	-47,7	-76,3	-88,0	-100,0	-100,0	-100,0	Manchester
		Dedicated lane (fixed)	-	-21,9	-49,1	-76,5	-88,3	-	-	-	
	Parking price regulation	Baseline	0,0	-19,3	-38,8	-59,0	-79,2	-98,8	-98,9	-98,9	Santander
		Adjusted parking behaviour	-	-17,8	-40,0	-58,6	-78,5	-98,8	-98,8	-98,8	
	Replacing on-street parking	Baseline	0,0	-19,6	-49,5	-77,4	-87,5	-97,6	-97,4	-97,5	Leicester
		Removing half of spaces	-5,6	-24,7	-51,2	-78,6	-88,2	-97,6	-97,7	-97,4	
		Driving lanes	-13,3	-30,6	-56,2	-81,0	-89,2	-97,2	-97,2	-97,2	
		Pick-up/drop-off points	-9,7	-24,8	-52,7	-79,3	-88,7	-97,5	-97,6	-97,5	
		Public spaces	-13,0	-29,7	-55,5	-80,9	-89,0	-97,2	-97,2	-97,2	
		Cycling lanes	-11,7	-30,3	-55,5	-81,0	-89,1	-97,3	-97,2	-97,2	
	Automated ride sharing (20% of demand)	Baseline	0,0	-20,9	-49,8	-77,0	-88,6	-100,0	-100,0	-100,0	Manchester
		20% willing to share	-	-22,0	-49,9	-77,1	-88,6	-100,0	-100,0	-100,0	
		100% willing to share	-	-19,4	-47,8	-75,8	-88,0	-100,0	-100,0	-100,0	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	-20,7	-48,8	-76,9	-88,6	-100,0	-100,0	-100,0	Manchester
		GLOSA on 3 Intersections	0,0	-20,8	-48,7	-76,9	-88,6	-100,0	-100,0	-100,0	

Looking at the different **baselines** estimated, all networks showed a similar nearly 100% reduction in expected emissions. Of the cities, the three Manchester networks show the largest reductions at full CAV penetration, while the Leicester simulation ends with a slightly lower reduction at full penetration. These variations are largely due to emissions from a small number of public transport buses, which are not simulated to be electric vehicles and are more present in the Leicester and Santander networks.

The sub-use case **dedicated lanes for CAVs** shows that a dedicated CAV-lane does not have much additional benefit in terms of reduced CO_2 emissions when compared to the baseline. As with the baseline, the environmental impacts of increased CAV penetration rate are positive. These results support previous findings in the literature as mentioned in section 2.3.4.

The second sub-use case, **parking price regulation**, shows a similar trend in CO_2 emissions for the baseline and the scenario "adjusted parking behaviour." Because only CAVs adopt the adjusted parking behaviour, behaviour of the CO_2-emitting human-driven vehicles remains largely unchanged. Both scenarios show an over 98% reduction in emissions.

The sub-use case dealing with **replacing on-street parking** shows a decrease in CO_2 emissions with the implementation of all SUC scenarios (removing half on-street parking spaces, replacing with driving lanes, replacing with pick-up/drop-off points, replacing with public spaces, and replacing with cycling lanes). Comparing the parking removal scenarios with the baseline, it is clear that once the levels of human-driven vehicles drop to 20% and below, the removal of parking spaces shows no added benefit in terms of CO_2 emissions. However, at lower CAV penetration rates, the removal of on-street parking leads to a larger reduction in emissions than the baseline scenario. This is likely related to the reduction in traffic congestion (see Section 3.2.1) in the network resulting from the removal of on-street parking spaces. For the two SUC scenarios in which on-street parking spaces are still partially used (removing half of the on-street parking spaces and replacing with pick-up/drop-off points), the difference from baseline is correspondingly lower.

The **automated ride sharing** (ARS) SUC is expected to be beneficial for CO_2 emissions if drivers of non-CAV/non-electric vehicles participate in ARS, mainly due to trip sharing reducing the total vehicle kilometres travelled. Since CAV vehicles are assumed to be electric and therefore have limited/no impact on emissions, ARS were predicted to have little or no added impact at high CAV penetration rates. Therefore, the results show a similar trend in CO_2 emissions throughout all scenarios (baseline, 20% of demand & 20% willing to share, and 20% of demand & 100% willing to share). Of all the estimated ARS scenarios (see Appendix D.1), most scenarios showed a slightly reduced environmental benefit at lower CAV penetration rates compared to the baseline. This includes the scenario of serving 20% of demand with 100% willingness to share. The exception to this finding is the 20% of demand & 20% willingness to share scenario, which increases congestion due to the high number of ARS vehicles travelling in the network. This congestion serves to reduce the number of human-driven vehicle kilometres within a simulation run and therefore the predicted CO2 emissions. This finding is therefore more related to specific characteristics of the microsimulation method and does not necessarily represent an improvement in environmental performance. In general, the network effect of 20% of all private vehicle trips switching to ARS on overall emissions is negligible in the modelled scenarios.

Like in the previous sub-use cases, the **GLOSA** scenarios have a similar trend in reducing and eventually eliminating road related CO_2 emissions. However, when compared to the baseline, GLOSA as simulated here, has no real added benefits in terms of reducing emissions. Because GLOSA was implemented on a small scale (3 intersections) in the simulation, the effect on traffic in the overall network is not large enough to be seen back in a change in CO2 emissions compared to the baseline electrification trend.

In summary, increasing penetration levels of (electric) CAVs are expected to progressively reduce emissions as they replace combustion engines in the vehicle fleet. Of the SUCs evaluated here, only replacing on-street parking shows potential to further reduce emissions compared to the baseline scenario when penetrations of CAVs are relatively low.

3.1.2 Environment: Delphi results

Table 3.3 presents the estimated impacts on energy efficiency for each SUC-scenario given different CAV penetration rates and as estimated by experts in the Delphi study. Because a different panel of experts was consulted for each SUC (in order to keep questionnaire length manageable), baseline estimates also vary across SUCs. For any given impact, if the baseline estimates observe similar trends, experts were likely to be more in agreement with their expectations. A high amount of variation across baselines suggests the expert groups had more divergent expectations. For more information, see Appendix A.

From these results it is clearly evident that the estimates from the Delphi study are of a totally different magnitude than the emission reduction estimates (Section 3.1.1). This is in itself strange since emissions and energy efficiency are closely related. The difference is estimate size may well be explained by the different approaches in developing the estimates and the details available to define the baseline and SUC scenarios.

Table 3.3 Estimated impacts of CAVs on energy efficiency using Delphi method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs.

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet					
			0	**20**	**40**	**60**	**80**	**100**
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
Energy efficiency	Road use pricing	Baseline	0,0	-1,9	-3,8	3,7	9,9	7,6
		Empty km pricing	-	6,9	6,9	6,9	8,8	8,8
		Static toll	-	7,5	9,2	9,2	7,4	5,6
		Dynamic toll	-	13,1	13,1	12,7	12,7	12,7
	Dedicated lanes for CAVs	Baseline	0,0	0,3	-3,7	0,3	0,3	4,9
		Dedicated CAV lane (fixed)	-	-1,1	-2,9	3,7	5,4	6,8
		Dedicated CAV lane (dynamic)	-	4,2	4,2	6,4	6,3	6,3
	Parking price regulation	Baseline	0,0	6,0	14,0	23,1	25,4	30,6
		Adjusted parking behaviour	-	2,3	4,6	8,0	8,7	10,3
	Replacing on-street parking	Baseline	0,0	0,3	4,4	11,3	12,5	12,9
		Space for public use	-	6,8	8,8	10,8	10,8	13,3
		Driving lanes	-	-3,7	-3,8	-6,1	-2,1	-2,7
		Pick-up/drop-off	-	-10,2	-3,8	-3,6	-2,6	-7,1
	Automated ride sharing	Baseline	0,0	9,8	10,3	11,1	14,2	14,2
		Automated ridesharing	-	6,3	9,8	13,8	20,0	20,0
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	9,8	10,3	11,1	14,2	14,2
		GLOSA	-	9,4	14,8	18,7	27,9	27,9

For the **baseline scenarios**, the Delphi experts estimate that increasing penetration of CAVs will lead to an improvement of roughly 5-31% in energy efficiency across all considered SUCs. Expert groups were in agreement that at high CAV penetration rates, an improvement in energy efficiency is expected, although some predicted a slight decrease initially at lower penetration rates. (20-40% CAVs).

Regarding the policy interventions, the highest additional improvement is expected in the GLOSA sub-use case, where experts estimate that the implementation of GLOSA will lead to an additional benefit in energy efficiency (e.g. at 100% CAV penetration GLOSA improves the baseline estimate from 14% to 28%). For a few scenarios regarding parking price regulation, replacing on-street parking, or road use pricing, fewer benefits are expected than in the baseline.

In the **road use pricing** SUC, the "dynamic toll" scenario is estimated to further improve energy efficiency the most at all penetration levels. Introducing a dynamic toll in situations where 20-100% of the vehicles are electric CAVs is expected to further improve energy efficiency by 3-17% more than baseline values. Both the static and dynamic tolls are expected to have the most added benefit when human-driven vehicles still make up around half of the vehicle fleet, while empty kilometre pricing is expected to become more beneficial at higher CAV penetration levels.

For **dedicated lanes for CAVs**, although initially a higher improvement in energy efficiency is observed with the "dynamic dedicated lane", at penetration rates higher than 60%, the "fixed dedicate lane" has a slightly higher positive impact on energy efficiency.

For the **parking price regulation** scenarios, it is interesting that the baseline scenario has a much higher positive impact (31%) compared to the "adjusted parking behaviour" scenario (10%) where automated vehicles would largely avoid parking in city centres and instead drive around empty or leave the centre to park. Especially the "drive around" scenario (see Appendix D) is predicted to have a negative effect on energy efficiency.

Experts in the Delphi survey estimate that **Replacing on-street parking** with "space for public use" will have a similar or slightly higher positive impact on energy efficiency compared to the baseline. However, experts predict that replacing on-street parking with a "driving lane" or "pick-up/drop-off" spaces for shared vehicles will have a negative impact on energy efficiency.

The estimates for the **Automated ride sharing** and **GLOSA** sub-use cases also indicate a higher positive impact on energy efficiency compared to their baseline cases. For both sub-use cases, especially at higher CAV penetration rates, the introduction of these SUCs is expected to have an additional positive impact.

To summarise, compared to the baseline with only human-driven vehicles, Delphi experts estimate that the introduction of most sub-use case scenarios will result in an improvement of energy efficiency. However, this improvement is in most cases similar to the expected **baseline** improvement, suggesting that experts do not expect most of these interventions to have a large additional effect on energy efficiency (over and above what is expected from increased CAV penetration). SUC scenarios like dynamic toll, automatic ride sharing and GLOSA are estimated to have additional positive impacts for energy efficiency whereas replacing on-street parking with driving lanes or pick-up/drop-off points are estimated to have a detrimental effect.

3.2 Impacts on mobility

This section presents the estimated impacts that increasing levels of CAVs and the introduction of six SUCs considered in WP6 could have on mobility. Twelve indicators were used to evaluate the impacts (*Table 3.4*). The methods used to evaluate these impacts are microsimulation, mesosimulation, system dynamics and Delphi.

Table 3.4: Mobility impact definitions

Impact	Definition	Methodology
Travel time	Average duration of a 5 Km trip inside the city centre (all traffic)	Microscopic simulation / Mesoscopic simulation / Delphi*
Access to travel	The opportunity of taking a trip whenever and wherever wanted (10 points Likert scale)	Delphi
Amount of travel per person	Kilometres of travel per person in an area (all traffic)	Mesoscopic simulation / Delphi*
Total kilometres travelled (vehicle km)	Total vehicle kilometres travelled in the network (all traffic)	Microscopic simulation
Congestion	Average delays to traffic (seconds per vehicle-kilometre) as a result of high traffic volume (all traffic)	Microscopic simulation
Modal split using active travel	% change in network trip distance (all traffic) made using active (walking, cycling) transportation	Delphi
Modal split using public transport	% change in network trip distance (all traffic) made using public transportation % of trip distance made using public transportation	Delphi
Shared mobility rate	% change in number of trips made sharing a vehicle with others	Delphi
Modal split Vienna: Active modes	% of Vienna network trip distance (all traffic) made using active transportation (walking, cycling)	System dynamics
Modal split Vienna: Public transport	% of Vienna network trip distance (all traffic) made using public transportation	System dynamics
Vehicle utilisation rate	% of time a passenger vehicle is in motion (not parked)	Delphi
Vehicle occupancy	% of kilometres a vehicle is occupied by passengers	Delphi

** The Delphi method was also used to estimate a simplified form of these impacts but is excluded from this overview. For Delphi results on travel time see Haouari et al. (2021) and for amount of travel see Sha et al. (2021).*

The modal split results were calculated using two methods: Delphi and system dynamics. The Delphi results discuss the general expected development (in relative percentages) according to the expert panel (see Section 3.2.4) for active modes (walking & cycling), public transport, as well as shared mobility. System dynamics estimated the effects of on the modal split of the city of Vienna, Austria (see Section 3.2.3).

3.2.1 Mobility: Microsimulation results

Table 3.5 provides estimates of the impacts on mobility (measured in travel time, amount of travel and congestion, see *Table 3.4*) as obtained from the microsimulation model results for the various SUC intervention scenarios. Important to note is that each SUC was estimated on a different road network taken from one of three cities (Manchester and Leicester in the UK and Santander in Spain) in order to divide the workload. As a result, baseline estimates vary across SUCs due to differences in the networks (e.g. road geometry, traffic volumes). Even within the same city (Manchester), baseline estimates can vary due to analysing different sections of the network for each SUC. The networks are described in Appendix C. The results across the modelled networks show an expected range of results and serve as indicative given the type and size of network modelled. For the smaller networks used (especially from Santander for parking price regulation as well as the GLOSA network) more random variation in the simulation can be expected to be more visible in the results. For transferability of results purposes, it is important to consider networks and conditions similar to those modelled in Levitate (see the underlying reports for details).

Table 3.5 Estimated impacts of CAVs on mobility using microsimulation method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs (100-0-0).

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (Human-driven vehicle – 1st Generation CAV – 2nd Generation CAV)								
			100-0-0	**80-20-0**	**60-40-0**	**40-40-20**	**20-40-40**	**0-40-60**	**0-20-80**	**0-0-100**	
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%	%	%	**City**
Travel time	Dedicated lanes for CAVs	Baseline	0,0	0,0	7,2	-0,1	5,3	4,2	1,8	1,0	Manchester
		Dedicated lane (fixed)	-	1,6	0,7	2,8	3,0	-	-	-	
	Parking price regulation	Baseline	0,0	28,0	18,6	24,2	6,0	16,9	0,4	-0,1	Santander
		Adjusted parking behaviour	-	16,3	19,5	16,4	14,4	25,9	19,4	23,3	
	Replacing on-street parking	Baseline	0,0	4,4	2,6	-7,3	-2,1	-4,7	-5,2	-6,5	Leicester
		Removing half of spaces	-3,4	-7,0	-6,4	-10,8	-12,1	-12,8	-8,0	-10,9	
		Driving lanes	-30,7	-30,9	-32,7	-35,6	-35,2	-34,2	-34,3	-34,4	
		Pick-up/drop-off points	-8,7	-10,1	-13,6	-18,0	-15,3	-15,1	-16,1	-16,6	
		Public spaces	-29,6	-28,6	-30,1	-33,8	-32,3	-32,0	-31,7	-32,9	
		Cycling lanes	-28,4	-29,7	-30,2	-33,9	-33,6	-32,2	-32,6	-32,2	
	Automated ride sharing (20% of demand)	Baseline	0,0	-1,0	-3,2	-4,9	-3,1	1,2	-1,9	-2,2	Manchester
		20% willing to share	-	8,1	5,7	6,4	10,6	13,1	14,4	12,7	
		100% willing to share	-	4,1	6,5	5,5	1,6	3,9	2,7	-1,5	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	0,4	0,0	0,2	1,2	2,2	3,6	3,7	Manchester
		GLOSA on 3 Intersections	0,0	0,0	-0,5	-0,9	-0,1	0,0	2,0	1,9	
Total kilometres travelled (vehicle km)	Dedicated lanes for CAVs	Baseline	0,0	-4,8	-0,1	-3,5	-2,7	-9,4	3,6	0,7	Manchester
		Dedicated lane (fixed)	-	-0,9	-0,9	0,9	-8,4	-	-	-	
	Parking price regulation	Baseline	0,0	-27,4	-31,0	-23,3	-34,1	-22,6	-24,3	7,2	Santander
		Adjusted parking behaviour	-	-32,4	-42,3	-28,9	-39,1	-32,6	-26,9	-20,9	
	Replacing on-street parking	Baseline	0,0	-2,4	-11,0	8,5	-1,7	-9,1	2,0	-6,3	Leicester
		Removing half of spaces	-9,2	-6,2	-7,0	-7,2	-5,4	-5,5	-9,0	1,7	
		Driving lanes	10,6	11,3	8,7	11,6	11,1	12,2	12,4	13,1	
		Pick-up/drop-off points	-15,0	-1,4	-5,6	-2,9	-16,6	-2,8	-7,3	-1,8	
		Public spaces	9,6	10,8	8,8	11,3	10,2	11,9	12,0	11,5	
		Cycling lanes	11,1	10,7	10,1	9,1	11,9	8,0	11,7	12,2	
	Automated ride sharing (20% of demand)	Baseline	0,0	-6,0	-13,0	-8,3	-5,9	-5,0	-9,9	-8,1	Manchester
		20% willing to share	-	-7,0	-11,7	-13,6	-19,0	-17,2	-12,9	-9,1	
		100% willing to share	-	-10,7	-9,5	-7,1	-2,2	-1,3	0,1	4,2	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	0,0	-0,4	-0,4	-1,1	-0,5	-1,6	-0,9	Manchester
		GLOSA on 3 Intersections	0,0	0,0	-0,3	-0,4	-1,0	-0,3	-1,5	-0,8	
Congestion	Dedicated lanes for CAVs	Baseline	0,0	-1,2	9,7	-3,9	4,2	-0,7	-4,4	-7,1	Manchester
		Dedicated lane (fixed)	-	0,7	-1,7	0,3	-0,8	-	-	-	
	Parking price regulation	Baseline	0,0	37,2	24,5	31,0	6,9	20,1	-1,3	-3,1	Santander
		Adjusted parking behaviour	-	22,2	26,2	20,9	18,5	32,7	23,7	28,6	

	Replacing on-street parking	Baseline	0,0	5,7	2,4	-12,9	-6,2	-10,8	-11,3	-13,4	Leicester
		Removing half of spaces	-5,0	-10,8	-10,8	-17,9	-20,6	-22,5	-15,7	-19,9	
		Driving lanes	-44,8	-45,8	-49,2	-54,2	-54,3	-53,8	-54,0	-54,1	
		Pick-up/drop-off points	-12,5	-15,5	-21,2	-28,5	-25,3	-25,9	-27,3	-28,1	
		Public spaces	-43,1	-42,5	-45,4	-51,6	-50,1	-50,6	-50,2	-51,9	
		Cycling lanes	-41,4	-44,1	-45,6	-51,7	-52,0	-50,9	-51,5	-50,8	
	Automated ride sharing (20% of demand)	Baseline	0,0	-2,5	-7,3	-11,6	-9,7	-4,3	-9,7	-11,4	Manchester
		20% willing to share	-	12,7	7,5	6,9	12,6	15,8	17,5	14,6	
		100% willing to share	-	4,8	7,8	5,3	-2,1	0,6	-1,8	-8,6	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	-1,1	-4,5	-6,3	-6,1	-6,1	-2,8	-2,4	Manchester
		GLOSA on 3 Intersections	0,0	-1,9	-5,7	-8,7	-9,2	-11,2	-6,5	-6,5	

Travel time

Looking at the impacts on travel time across the 3 different networks used in the microsimulation, a -6,5% to +3,7% effect on average travel times is found in the **baseline** scenario at full penetration of CAVs (0-0-100). The effect of automation on average travel times is therefore predicted to vary somewhat depending on the network modelled. For the larger networks (dedicated lanes, replacing on-street parking, and automated ride sharing), only slight baseline changes are predicted in suburban Manchester and while a moderate reduction in travel time is predicted for central Leicester. Implementing the sub-use case policy interventions in the network showed a variety of effects: from a large additional reduction in average travel times of up to -35% (at 80-20-0 and 60-40-0 implementation) by replacing parking spaces with driving lanes in Leicester to large increases in travel time of up to +23% by introducing parking pricing policies that dramatically affect parking utilisation in Santander.

Introducing **dedicated lanes for CAVs** is predicted to have a marginal positive effect on travel times (less increase) when compared to the baseline at some low penetration levels of 1st generation CAV (60-40-0 and 20-40-40). When roughly equal numbers of CAV and non-CAVs use the network travel times may, however, increase compared to the baseline. In the stages of penetration where both CAVs and non-CAVs share the road, the baseline scenario shows an increase in travel time (up to 7%). The dedicated lane for CAVs seems to reduce these congesting effects of interactions between 1st generation CAVs and human-driven vehicles particularly when there is a large share of both vehicle types in the network (60% human-driven vehicles, 40% 1st generation CAV).

For **parking price regulation**, the implementation of an "adjusted parking behaviour" increases travel time by up to 26% (compared to 17% in the baseline, an effective further increase in travel time of 9% as a result of the pricing policy adopted). In this scenario, the majority of CAVs which would otherwise park at the destination instead choose one of the following options due to higher parking prices at the destination: return to origin (22%), drive outside centre to park (45%), or drive around until the passenger is ready to be collected (20%). While increases are also seen in the baseline for the Santander network, these increases are mostly less than when parking price regulation is implemented especially once human-driven vehicles make up 20% or less of the vehicle fleet. At high CAV penetrations, more of the vehicle fleet exhibits the adjusted parking behaviour, therefore causing more congestion and increases in travel time due to the larger number of empty kilometres driven.

In general, **replacing on-street parking** with any of the scenarios (removing half on-street parking spaces, replacing with driving lanes, replacing with pick-up/drop-off points, replacing with public spaces, and replacing with cycling lanes), improves travel time. In the microsimulation, parking manoeuvres are a source of congestion which can increase travel times; therefore, the scenarios where on-street parking is completely removed (replaced with driving lanes, public space, or cycling lanes) have the largest effects on travel time. The scenario that improves travel time the most is "replacing on-street parking with driving lanes" which is expected since it provides more capacity. The baseline scenario also improves travel time but much less than the sub-use case scenarios.

Automated ride sharing is not predicted to improve travel times compared to the baseline scenario. This can largely be explained by the increase in empty kilometres driven with implementation of an automated ride sharing system (see Section 2.4.5), as the automated ride sharing vehicles circulate in the network to pick up the next passenger. Even when willingness to share is high, not every trip will be suitable for sharing as the choice to share cannot cause large delays to the other passenger(s). The additional empty kilometres therefore have the potential to overcompensate for benefits due to trip sharing, especially when willingness to share is low, and can cause increased congestion and travel times. In addition, travel times may increase slightly during shared trips due to picking up and/or dropping off additional passengers. The baseline scenario has a small improvement in travel time, but the sub-use case scenarios mostly increase travel time. For higher CAV penetration rates the "20% willing to share" has a higher travel time impact (between 13% and 14%) compared to the "100% willing to share" scenario which has a slight improvement (1,5%) in travel time at the 0-0-100 penetration rate. This suggests that the willingness of users of automated ride sharing to share trips with other travellers can have an important effect on the traffic situation by reducing the number of automated taxi vehicles and trips present in the network.

The last sub-use case applied to travel time is **GLOSA**. For the baseline, travel time increases as CAV penetration rate increases. However, implementing the "GLOSA on three intersections" initially reduces travel time, and only increases travel time at a penetration rate of 0-20-80 (2%), but not as high as the baseline scenario (4%). It must be mentioned that GLOSA affects only 3 intersections in the network and therefore the overall network effects are small.

Total kilometres travelled
The second mobility indicator estimated with microsimulation was the total kilometres travelled in the modelled networks. As travel demand remains constant in the microsimulation, an increase or decrease in total kilometres travelled generally reflects changes to the traffic situation: when traffic flows more smoothly with less congestion, more trips are able to be completed in one simulation period. Therefore, an increase in kilometres travelled is considered here to be a positive development (increase is indicated in green in *Table 3.5*) as it represents an improvement in mobility and accessibility of the network. However, an actual increase in total kilometres travelled by motor vehicles due to an increase in travel demand or a modal shift could also bring about negative environmental and/or societal externalities. More kilometres travelled may, for example, use more energy, represent a modal shift from public transport/active modes to private vehicles, increase exposure to traffic safety risks, or use more public space. These potential negative effects are not considered in these results as changes to travel demand or modal split are outside the scope of microsimulation.

Across the different networks studied, the **baseline** impacts for the different SUCs show a change in total kilometres travelled at full penetration (0-0-100) of between +7% (parking price regulation network) and -8% (automated ride sharing network) when compared to the starting point with only human-driven vehicles (100-0-0). Across the different penetration rates, total kilometres travelled vary without a clear trend relating to increasing CAV penetration. As with travel time and congestion, the effect of automation on travelled kilometres is predicted to vary depending on network conditions. The largest baseline variations in total kilometres travelled are seen in the Santander network used for parking price regulation; this may be related to the relatively small size of the network used (see Appendix C).

Looking at the **dedicated lanes for CAVs** SUC, implementing a "fixed dedicated lane" shows a similar trend to the baseline which varies between a slight decrease and a slight increase in kilometres travelled. The last three penetration rates cannot be compared because no values were calculated for the "fixed dedicated lane" as there is 100% CAV penetration and therefore all lanes are only used by CAVs.

The **parking price regulation** scenario "adjusted parking behaviour", shows a large reduction in the total kilometres travelled (ranging from 30% to 42%) across different penetration rates. As mentioned, a decrease in kilometres travelled is seen as a negative impact since it is largely caused by congestion in the network and therefore suggests a decline in accessibility and mobility. In the baseline, there is also a decrease in kilometres travelled except for the last penetration level (0-0-100), where there is a 7% increase in kilometres travelled. At all penetration rates, the shift from parking in the city centre of Santander (baseline) to driving around or parking elsewhere (adjusted parking behaviour) appears to increase the total amount of congestion in such a way that less kilometres can be travelled during a simulation period.

For the **replacing on-street parking** sub-use case, different results are observed per scenario. For the baseline scenario there is a mostly negative development in total kilometres travelled. Out of the five scenarios in this sub-use case, two of the scenarios, "removing half on-street parking spaces", and "replacing with pick-up/drop-off points" also show a general negative impact on kilometres travelled. The other three scenarios, "replacing with driving lanes", "replacing with public spaces", and "replacing with cycling lanes" show an increase in total kilometres travelled of around 12%. In these three scenarios, on-street parking is completely removed, which when present can be a source of a congestion (leading to fewer kilometres travelled in a simulation period).

In general, **automated ride sharing** is expected to lead to an increase in vehicle kilometres, due to the empty repositioning of vehicles to pick up passengers potentially being larger than the reductions due to the trips which can actually be shared. In the microsimulation results, scenarios with higher willingness to share (see Appendix D for all scenarios) show this expected increase in kilometres travelled compared to the baseline results. In the "100% willing to share" scenario, automated ride sharing is predicted to increase total kilometres travelled by 4% at full penetration compared to a decrease of -8% in the baseline. When willingness to share is lower, however, significantly increased delays due to congestion in the network reduce the number of trips and vehicle kilometres which can be completed within a simulation period. This leads, somewhat counterintuitively, to a decrease in kilometres travelled in the "20% willing to share" scenario. The results suggests that trips with a higher willingness to share are expected to improve traffic flow.

The last sub-use case for which the impact on total kilometres travelled was estimated is **GLOSA.** For this SUC it is predicted that in both the baseline and "GLOSA on three intersections", the total kilometres travelled slightly decreased (up to less than 2%) and the difference between baseline and GLOSA is marginal. Implementation of GLOSA is therefore predicted to have little additional effect on kilometres travelled.

Congestion

The final mobility indicator estimated with microsimulation is congestion, measured in terms of delays (seconds) due to traffic congestion per vehicle-kilometre travelled for all traffic in the network. The different **baseline** estimations show mostly a decrease in congestion expected with the introduction of automated vehicles, especially once human-driven vehicles make up 40% (40-40-20) or less of the vehicle fleet. In the network of Santander, some larger increases in congestion are seen when human-driven and/or 1st generation CAVs still make up a large portion of the vehicle population. As mentioned before, this may be due to the small size of the network as well as the types of roads in this city centre network where congestion due to mixed traffic conditions may be more visible.

The results from the **dedicated lanes for CAVs** sub-use case show a general decrease in congestion as CAV penetration rates increase in the baseline scenario, and mixed results with the inclusion of a "fixed dedicated lane." The inclusion of the dedicated CAV lane leads to a small reduction in congestion compared to its baseline values for two out the four penetration rates for which a dedicated CAV lane was considered; for the other two penetration rates, slightly more congestion was found. Therefore, no clear effect is predicted for dedicated CAV lanes on congestion.

The **parking price regulation** SUC shows that congestion levels in the baseline scenario increase markedly in the penetration rates with mixed human-driven and CAV traffic. Only once the penetration levels of 2nd generation CAVs reach 80% do congestion levels decrease by between 1 and 3% in the baseline. The "adjusted parking behaviour" scenario shows some lower congestion levels than the baseline when 40% or more of the vehicle fleet is still human-driven; however, as penetration levels of CAVs increase, the scenario with adjusted parking behaviour shows higher levels of congestion than the baseline. As discussed for travel time, in the adjusted parking behaviour scenario, the majority of CAVs which would normally park at the destination now travel to somewhere else to park or drive around while waiting. These alternatives are therefore predicted to cause some additional traffic congestion compared to the baseline where vehicles park at their destination.

Replacing on-street parking shows a promising impact on congestion. The implementation of each of the five SUC scenarios results in a decrease in congestion of between 20% and 54%, all substantially more than estimated for just the baseline. High congestion reduction levels can even be seen at low CAV penetration rates in three scenarios where on-street parking is completely removed: "replacing with driving lanes", "replacing with public spaces", and "replacing with cycling lanes". As discussed earlier, in the microsimulation, parking manoeuvres are a source of congestion. Therefore, removing these manoeuvres completely results in a larger reduction in congestion. The other two scenarios remove only some of the parking manoeuvres and therefore have a smaller, yet still sizeable, effect.

As discussed for travel time and total kilometres travelled, **automated ride sharing** is expected to cause some increased congestion, especially when the willingness to share trips are low. This increased congestion is largely related to the additional empty vehicle kilometres (see Section 2.4.5) necessary to pick up their next passenger. While trip sharing can reduce some of the un-occupied kilometres, not all trips will be suitable for combining and not all passengers are expected to be interested in sharing their trips. This results in an overall increase in congestion in the "20% willing to share" scenario of up to 18%. This while in the baseline scenario, increasing CAV penetration is predicted to reduce congestion by up to 11%. When all ride sharing users (20% of the total travel demand) are willing to share their trips with other ride sharing users within the allowable detour time (5-10 minutes), congestion results much closer to the baseline reduction are reached: the "100% willing to share" scenario shows a decrease in congestion of -2% to -9% once 2nd generation CAVs make up 80% or more of the vehicle fleet, only slightly higher than for the baseline (-10% to -11%).

The last sub-use case used to evaluate the impact on congestion using microsimulation is **GLOSA**. Both the baseline and "GLOSA on three intersections" decrease congestion, while the "GLOSA on three intersections" scenario has a slightly higher impact on reducing congestion: an almost 7% reduction, compared to the 2% in the baseline at 0-0-100 penetration rate. GLOSA is therefore expected to have a positive effect on congestion.

3.2.2 Mobility: Mesosimulation results

Table 3.6 summarises the impacts on average travel time and amount of travel as obtained from the mesosimulation method. These mobility impact estimates were derived for one SUC, namely road use pricing (RUP). RUP was implemented in the mesosimulation of the Vienna road network using both a static toll (10-euro fee to enter the city centre by private vehicle) and a dynamic toll (implemented as a kilometre price of 1,4 euros per km travelled by private vehicle in the city centre and equating to 10 euros to cross the city). The RUP scenarios are compared to a baseline with no fee to enter the city centre. In Appendix D, further scenarios with different toll levels can be found.

Table 3.6 Estimated impacts of CAVs on mobility using the mesosimulation method. Percentages indicate the difference relative to the impact's Baseline at 0% penetration of CAVs (100-0-0).

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (Human-driven vehicle – 1st Generation CAV – 2nd Generation CAV)								
			100-0-0	**80-20-0**	**60-40-0**	**40-40-20**	**20-40-40**	**0-40-60**	**0-20-80**	**0-0-100**	
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%	%	%	**City**
Average travel time (5km trip)	Baseline	0 euro	0,0	0,2	0,0	-0,1	-0,3	-0,5	-0,4	-0,5	Vienna
	Road-use pricing	Static toll: 10 euros	2,4	2,3	2,3	2,1	2,0	1,8	1,6	1,7	
		Dynamic toll: €1,4/km	4,2	3,8	3,8	4,0	3,8	3,7	3,6	3,7	
Amount of travel (per person)	Baseline	0 euro	0,0	0,0	-0,1	-0,1	-0,2	-0,2	-0,2	-0,2	
	Road-use pricing	Static toll: 10 euros	-0,1	-0,2	-0,2	-0,2	-0,3	-0,3	-0,3	-0,3	
		Dynamic toll: €1,4/km	0,2	0,2	0,1	0,1	0,2	0,1	0,1	0,1	

Similar to the microsimulation method, the mesosimulation keeps travel demand (activity patterns and locations) constant. However, unlike the microsimulation, the activity-based model used in the mesosimulation also takes into account potential modal shifts or changes in route choice. For this reason, the implementation of a toll to enter the city centre can potentially lead to travellers switching either their travel mode or their route to avoid the toll.

The results indicate that **average travel time** is higher throughout all penetration levels when a "dynamic toll: €1,4/km" is implemented, and slightly higher when a "static toll: 10 euros" is implemented compared to the baseline. In the baseline scenario, average travel time decreases slightly (up to 0,5%) as CAV penetration rates increase. This is due to travellers choosing to switch from private vehicle transport (which may be the fastest) to another toll-free mode, such as public transport, which may have a slightly longer travel time. The dynamic toll appears to have a stronger effect on this shift than the static toll.

The **amount of travel**, defined as the average distance travelled by a person on a weekday, shows a slight decrease in the baseline and "static toll: 10 euros" scenarios as CAV penetration rates increase, while the "dynamic toll: €1,4/km" indicates a small increase in the amount of travel (0,1 and 0,2 %). Neither road use pricing nor the development of CAVs appear to have a large impact on the average distance a person travels on a weekday. Because travel activity patterns (e.g. home – work – home) remain constant, a slight increase due to a modal shift similar to the increase in travel times might be expected; however, it appears that actual distances travelled do not increase with a mode shift as much as travel time does.

3.2.3 Mobility: System dynamics results

Table 3.7 shows the impacts of the SUCs on the modal split of active modes and public transport at different CAV penetration rates. The estimates derived from the results obtained by applying a system dynamics model to the road network of the city of Vienna. Four of the six sub-use cases are modelled with the system dynamics model: road use pricing, parking price regulation, replacing on-street parking, and automated ride sharing. These sub-use cases are expected to have more indirect/macroscopic level impacts which can be better captured by the system dynamics model. System dynamics, unlike microsimulation, takes into account the potential indirect influences of a modal shift due to implementation of the SUC measures. Modal split trends are indicated in terms of the percentage change from the starting share of trip distance (mode share at Baseline 0% CAVs). For example, a reduction in mode share from 20% to 10% of all travelled kilometres in Vienna would constitute a change of -50%.

Table 3.7 Estimated impacts of CAVs on modal split using system dynamics, measured in terms of percentage change of the starting modal split (Baseline; 0% CAVs)

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)					
			0	20	40	60	80	100
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
Modal split Vienna[1]: Active modes (Walking & Cycling)	Baseline	no policy intervention	0,0	0,0	-6,3	-18,8	-31,3	-56,3
	Road use pricing	Static toll: 10 euros	12,5	12,5	6,3	0,0	-6,3	-18,8
	Parking price regulation	Adjusted parking behaviour	18,8	18,8	12,5	12,5	0,0	-31,3
	Replacing on-street parking	Removing half of spaces	12,5	6,3	0,0	-12,5	-31,3	-56,3
		Replacing with driving lanes	18,8	12,5	12,5	0,0	-12,5	-37,5
	Automated ride sharing	20% of demand & 100% willing to share	-9,3	-12,4	-18,4	-28,2	-41,7	-61,3
Modal split Vienna[2]: Public transport	Baseline	no policy intervention	0,0	0,0	-2,1	-6,2	-10,4	-16,7
	Road use pricing	Static toll: 10 euros	18,8	18,8	14,6	10,4	8,3	-2,1
	Parking price regulation	Adjusted parking behaviour	-4,2	-6,2	-10,4	-14,6	-18,8	-12,5
	Replacing on-street parking	Removing half of spaces	0,0	-2,1	-6,2	-10,4	-12,5	-18,8
		Replacing with driving lanes	-8,3	-10,4	-20,8	-29,2	-35,4	-37,5
	Automated ride sharing[3]	20% of demand & 100% willing to share	14,6	13,8	10,2	6,5	3,5	-2,5

[1]Percentage changes refer to percentage of the initial 16% mode share of active modes (Baseline; 0% CAVs)
[2]Percentage changes refer to percentage of the initial 48% mode share of public transport (Baseline; 0% CAVs)
[3]Automated ride sharing is considered by system dynamics to be a form of public transport in the modal split

In the system dynamics model based on the city of Vienna, before implementation of CAVs or SUC policies active modes make up 16% of the modal split while public transport composes 48%. In the **baseline** estimation, both mode shares are predicted to decrease as CAV penetration increase: active mode share is expected to be cut in half (to roughly 7% of travel demand), while the share of public transport is predicted to decrease by 17% (resulting in a 40% mode share). In other words, CAVs are predicted to take a roughly equal share of travel kilometres away from both active modes and public transport (8% to 9% of the total travel demand), but because active modes began with a lower share of the travel demand, this results in a 56% reduction from the starting mode share. The effects of CAVs on the modal split are strong enough that, while some SUC interventions offset a portion of this decline, all SUC scenarios also predict at least a small reduction in active modes and public transport at 100% CAV penetration. These results suggest that CAVs will attract a large proportion of people currently walking and cycling or taking public transport to using some form of CAV transport, which is seen as an unfavourable development for environmental and public health reasons.

The introduction of the sub-use cases **road use pricing**, **parking price regulation**, and **replacing on-street parking with driving lanes** to an extent mitigate the negative impact of CAV penetration and seem to stimulate people to walk and cycle. At 0% CAV penetration, the mode shares of active modes after introducing these sub-use cases are between 13% and 19% higher than in the baseline (absolute mode shares of 18%-19%), meaning that initially they increase active mode share when compared to the baseline. As CAV penetration rates increase, the modal share of active modes decreases by only 19% to 38% of the starting value, which is higher than in the baseline (56% reduction). **Removing half of on-street parking spaces** shows a mixed effect on active mode use: initially, there is an increase in active modes compared to the baseline when CAV penetration is still less than 20% of the vehicle fleet. However, as CAV penetration increases, the benefits of removing half of on-street parking spaces diminish and the SUC results in a similar decrease to the baseline results. Lastly, **automated ride sharing** is predicted to reduce the use of active modes of travel compared to the baseline at all penetrations of CAVs. In an entirely human-driven context, walking and cycling accounts for a 9% reduction in share of travelled kilometres compared to the baseline (a decrease from 16% to 14,5% in absolute mode share).

Regarding the mode share of public transport, **road use pricing** and **automated ride sharing** are expected to increase public transport use compared to the baseline at every penetration rate of CAVs. While the baseline shows a 17% reduction at full CAV penetration, implementing road use pricing results in only a 2% reduction (and an initial increase of 19% before CAVs) while automated ride sharing results in a 3% final reduction (and a 15% increase before CAVs). The increased modal share in public transport with the automated ride sharing service is due to the fact that this new mode is included as part of public transport. Road use pricing, on the other hand, is predicted to discourage private vehicle use due to the increased costs associated with entering the city of Vienna leading to some travellers choosing public transport over a private automated or human-driven vehicle. **Parking price regulation** shows a mostly negative impact on public transport use, leading to lower mode shares than the baseline at all penetration rates except for 100% CAV penetration. This reduction in public transport use may be related to reduced parking costs when vehicles avoid parking in high-cost areas by leaving the centre or driving around, while at 100% CAV penetration increased congestion may play a role in discouraging private vehicle use. **Replacing on-street parking** is also predicted to negatively impact use of public transport, especially in the "replace with driving lanes" scenario which more than doubles the reduction in public transport use compared to CAVs alone. This is likely due to increased road capacity and large reductions in congestion, making private vehicle use a more attractive option and therefore attracting a share of public transport users.

3.2.4 Mobility: Delphi results

Table 3.8a & *Table 3.8b* summarise the impacts on mobility as estimated for the various SUC in the Delphi expert panel evaluation. The baseline values for each SUC differ because a different group of experts were asked for each SUC. Each expert group developed a baseline specific to their SUC, similar to the different networks used in the simulation methods. For any given impact, if the baseline estimates show similar trends, experts were likely more in agreement with each other's expectations. A high amount of variation across baselines suggests the different expert groups had different opinions on the estimates. For more information, see Appendix A.

Table 3.8a Estimated impacts of CAVs on Access to travel, modal split and shared mobility rate using the Delphi method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs.

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)					
			0	20	40	60	80	100
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
Access to travel	Road use pricing	Baseline	0,0	-1,8	0,0	3,5	12,8	23,0
		Empty km pricing	-	-7,5	-4,2	-2,5	-4,2	0,7
		Static toll	-	-7,6	-7,6	-4,1	-2,3	-2,3
		Dynamic toll	-	-7,9	-7,9	-3,7	0,0	3,8
	Dedicated lanes for CAVs	Baseline	0,0	-5,6	-1,8	-4,2	1,9	11,4
		Dedicated CAV lane (fixed)	-	5,8	2,7	8,2	5,8	9,9
		Dedicated CAV lane (dynamic)	-	7,2	11,9	11,6	11,8	16,6
	Parking price regulation	Baseline	0,0	2,3	11,9	21,8	35,5	50,9
		Adjusted parking behaviour	-	6,1	8,5	13,6	20,1	24,7
	Replacing on-street parking	Baseline	0,0	-8,8	-8,8	-10,8	-8,7	-11,3
		Space for public use	-	-6,5	-6,4	-7,7	-10,9	-15,6
		Driving lanes	-	-6,1	-6,2	-0,1	6,9	6,9
		Pick-up/drop-off	-	-1,4	0,4	0,3	0,3	0,9
	Automated ride sharing	Baseline	0,0	13,1	15,6	22,9	22,9	25,9
		Automated ridesharing	-	10,8	16,9	29,3	32,1	40,6
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	13,1	15,6	22,9	22,9	25,9
		GLOSA	-	3,4	3,4	3,4	0,2	0,2
Modal split: Active modes (Walking & cycling)	Road use pricing	Baseline	0,0	-5,6	-5,7	-12,2	-20,1	-20,1
		Empty km pricing	-	4,3	6,3	10,0	6,2	4,3
		Static toll	-	10,8	14,8	14,8	12,9	12,9
		Dynamic toll	-	-6,1	-6,1	0,1	0,1	2,5
	Dedicated lanes for CAVs	Baseline	0,0	-4,9	-4,9	-9,3	-9,3	-12,7
		Dedicated CAV lane (fixed)	-	-0,9	-2,1	-5,0	-5,5	-7,7
		Dedicated CAV lane (dynamic)	-	0,2	-3,2	-3,2	-3,2	-3,6
	Parking price regulation	Baseline	0,0	-13,2	-16,7	-28,1	-30,3	-35,2
		Adjusted parking behaviour	-	-5,5	-6,9	-6,1	-9,6	-11,1
	Replacing on-street parking	Baseline	0,0	-5,6	-9,6	-16,1	-21,2	-28,1
		Space for public use	-	6,7	8,8	18,4	27,0	31,5
		Driving lanes	-	8,8	9,3	7,4	9,4	9,4
		Pick-up/drop-off	-	-1,5	-1,4	3,4	3,4	8,3
	Automated ride sharing	Baseline	0,0	1,5	3,2	6,8	11,8	2,9
		Automated ridesharing	-	7,3	7,7	6,9	3,3	3,3
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	1,5	3,2	6,8	11,8	2,9
		GLOSA	-	-3,0	-4,6	-4,6	-4,6	-4,6

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)					
			0	20	40	60	80	100
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
Modal split: Public transport	Road use pricing	Baseline	0,0	-7,6	-9,6	-16,1	-26,1	-28,6
		Empty km pricing	-	5,6	7,5	5,4	3,7	3,7
		Static toll	-	16,9	20,8	15,0	13,2	15,6
		Dynamic toll	-	13,5	15,4	9,4	7,9	7,9
	Dedicated lanes for CAVs	Baseline	0,0	-3,7	-3,7	-11,6	-19,6	-24,6
		Dedicated CAV lane (fixed)	-	-4,3	-3,8	-10,7	-13,7	-17,5
		Dedicated CAV lane (dynamic)	-	-3,2	-4,9	-8,4	-13,7	-15,8
	Parking price regulation	Baseline	0,0	-6,5	-10,3	-9,7	-15,4	-17,7
		Adjusted parking behaviour	-	-5,4	-6,3	-4,6	-9,4	-9,5
	Replacing on-street parking	Baseline	0,0	-7,7	-9,7	-7,6	-11,8	-9,9
		Space for public use	-	4,3	8,1	17,0	20,3	26,5
		Driving lanes	-	7,9	8,0	5,0	0,8	1,7
		Pick-up/drop-off	-	-4,1	-10,5	-4,9	3,9	6,7
	Automated ride sharing	Baseline	0,0	-0,7	2,7	-6,4	-17,7	-17,7
		Automated ridesharing	-	6,5	7,4	2,5	-1,1	-7,2
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	-0,7	2,7	-6,4	-17,7	-17,7
		GLOSA	-	-4,6	-4,6	-4,6	-4,6	-7,8
Shared mobility rate	Road use pricing	Baseline	0,0	-0,9	6,1	13,5	17,2	23,4
		Empty km pricing	-	4,9	6,7	12,5	16,9	20,5
		Static toll	-	10,7	12,6	15,0	14,9	16,8
		Dynamic toll	-	12,4	14,4	17,8	22,0	23,9
	Dedicated lanes for CAVs	Baseline	0,0	4,2	10,3	18,8	30,5	35,5
		Dedicated CAV lane (fixed)	-	4,2	0,3	10,2	13,1	20,3
		Dedicated CAV lane (dynamic)	-	3,6	0,2	14,2	12,5	22,2
	Parking price regulation	Baseline	0,0	-3,7	2,3	13,8	18,1	27,0
		Adjusted parking behaviour	-	3,7	7,5	16,9	19,7	23,8
	Replacing on-street parking	Baseline	0,0	-5,6	-1,8	-4,2	1,9	11,4
		Space for public use	-	0,3	12,9	21,5	41,5	46,5
		Driving lanes	-	6,8	4,4	8,8	8,3	13,3
		Pick-up/drop-off	-	1,8	0,8	7,8	16,9	19,4
	Automated ride sharing	Baseline	0,0	3,8	7,3	16,6	27,2	40,4
		Automated ridesharing	-	6,3	15,2	25,0	36,0	40,3
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	3,8	7,3	16,6	27,2	40,4
		GLOSA	-	5,0	8,2	8,2	11,9	11,9

Access to travel

Access to travel is expected to improve with increasing CAV penetration in five of the six **baseline** estimations, by anywhere from 11% to 51% once all human-driven vehicles are replaced by automated vehicles. The experts consulted for replacing on-street parking, however, predicted that travelling would become more difficult with increasing CAVs leading to an 11% reduction in access to travel.

The sub-use case scenarios of **road use pricing**, **parking price regulation**, and **GLOSA** are expected to mitigate most of the benefits predicted in their baseline estimations, resulting in less improvement in access to travel when the policies are implemented in an increasingly automated transport system. For **dedicated CAV lanes** as well as **replacing on-street parking**, results differ per scenario. A "fixed" dedicated CAV lane is expected to result in a similar or slightly reduced access to travel compared to the baseline, while a "dynamic" dedicated CAV lane is predicted to improve access to travel compared to the baseline. Replacing on-street parking with "driving lanes" or to a lesser degree "pick-up/drop-off" spaces is expected to improve access to travel, while replacing the parking with "space for public use" is expected to reduce access to travel more than in the baseline.

Lastly, **automated ride sharing** is predicted to improve access to travel substantially, with experts predicting a 41% increase with automated ride sharing compared to a 26% increase in the baseline when all vehicles are CAVs.

Modal split

In nearly all of the **baselines** estimated, experts participating in the Delphi surveys predicted that increasing penetration levels of CAVs would lead to a declining modal share of walking and cycling (13% to 35% reduction). The exception is the baseline estimated in the automated ride sharing & GLOSA survey, in which a slight increase across the penetration rates is predicted. Regarding public transport use, for all of the baseline estimates a reduction is predicted as the presence of CAVs increases. At a 100% penetration rate of CAVs, experts predict a 10% to 29% reduction in the modal share of public transport.

For all six of the SUCs estimated, implementing the policy measures is expected to lead to more use of public transport compared to the baselines. For five of the SUCs, GLOSA being the exception, use of active modes is predicted to be higher than in the baselines. Regarding **road use pricing**, all forms of tolls are expected to increase the mode shares of both active modes and public transport with the largest effects predicted for a "static toll." The tolls are expected to have a slightly larger effect on increasing public transport use than on increasing walking and cycling. **Replacing on-street parking** with other facilities is also predicted to increase the mode shares of both public transport and active modes, especially when on-street parking is replaced with "space for public use."

Dedicated lanes for CAVs as well as **parking price regulation** are predicted to somewhat mitigate the decreases predicted due to CAVs, resulting in higher mode shares for both public transport and active modes compared to the baseline but nevertheless a small decline from the starting point with no automated vehicles. Of the two, parking price regulation has a slightly larger beneficial effect compared to its baseline.

Regarding **automated ride sharing** and **GLOSA**, this survey resulted in a positive baseline development for the mode share of walking & cycling, while public transport use was expected to reduce like in the other baselines. Implementing automated ride sharing was predicted to have a small or slightly positive effect on active modes compared to the baseline development. Automated ride sharing is also predicted to benefit public transport use, resulting in less of a decrease than in the baseline situation. GLOSA, on the other hand, is expected to slightly reduce the active mode share while public transport use is again predicted to decrease less than in the baseline.

The Delphi method also estimated the effects of increasing CAV penetration and the six SUCs on the usage of shared mobility. For all **baselines**, an increase is predicted in the shared mobility rate ranging from 11% to 40% at full penetration of CAVs. While no SUC interventions are expected to reduce shared mobility levels below the starting values (0% CAV), for most SUC scenarios less of an increase is predicted than in the baseline, suggesting that these policies have a negative effect on the use of shared mobility services.

Replacing on-street parking is the only SUC in which higher shared mobility rates are predicted for all scenarios, with an especially large increase predicted for replacing on-street parking with "space for public use." The only other scenarios expected to slightly increase the shared mobility rate are the **road use pricing** "dynamic toll," as well **automated ride sharing** at lower penetration rates of CAVs.

Vehicle utilisation & occupancy rate

Two additional impacts (vehicle utilisation rate and vehicle occupancy rate) were estimated in the Delphi study which are shown below in *Table 3.8b*.

With the exception of the **baseline** estimated in the dedicated lane for CAV survey, all of the baseline estimates for the remaining SUCs suggest that vehicle utilisation rates will significantly increase with increased levels of CAV penetration (19% to 50% increase). In the dedicated lane survey, mixed but small impacts were predicted for vehicle utilisation rate depending on the market penetration rate of CAVs. Compared to the respective baseline estimates, the **road use pricing**, **parking price regulation**, **replacing on-street parking**, **automated ride sharing** and **GLOSA** SUCs all seem to reduce the vehicle utilisation rate; in other words, vehicle utilisation rates are higher in the baseline than with the SUC being implemented. **Dedicated lanes for CAV** vehicles is the one intervention that is estimated to substantially improve vehicle utilisation compared to the baseline.

The final mobility impact estimated by the Delphi panel of experts was the effect on vehicle occupancy rate. Across the different expert groups consulted per SUC, **baseline** estimates vary from a moderate decrease (-9%) to a moderate increase (10%) in vehicle occupancy rates as CAVs increase to 100% of the fleet. Most of the SUC scenarios considered are expected to have a positive effect on vehicle occupancy, resulting in higher predictions than the respective baselines. Increased vehicle occupancy rates are predicted for **road use pricing**, **dedicated CAV lanes**, **parking price regulation**, and **automated ride sharing**. The effect of **replacing on-street parking** depends on the facility replacing parking spaces: "space for public use" and "pick-up/drop-off" spaces are expected to be beneficial for vehicle occupancy rates, while converting parking to "driving lanes" results in a similar decrease in occupancy to the baseline results. Lastly, **GLOSA** is expected to have a slightly negative effect on occupancy rates, resulting in less of an increase than in the baseline trend.

Table 3.8b Estimated impacts of CAVs on vehicle utilisation and vehicle occupancy rate using the Delphi method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs.

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)					
			0	20	40	60	80	100
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
Vehicle utilisation rate	Road use pricing	Baseline	0,0	2,7	6,4	21,6	36,8	45,8
		Empty km pricing	-	-1,4	-1,4	10,0	12,0	13,8
		Static toll	-	2,9	6,7	8,6	12,8	14,7
		Dynamic toll	-	-1,8	1,9	9,9	17,6	17,6
	Dedicated lanes for CAVs	Baseline	0,0	-1,2	9,7	-3,9	4,2	-0,7
		Dedicated CAV lane (fixed)	-	5,5	4,8	11,5	17,2	22,4
		Dedicated CAV lane (dynamic)	-	3,6	0,2	12,4	9,0	18,6
	Parking price regulation	Baseline	0,0	2,8	12,1	22,8	35,9	50,4

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)					
			0	20	40	60	80	100
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
		Adjusted parking behaviour	-	7,0	10,4	20,5	26,0	32,4
	Replacing on-street parking	Baseline	0,0	2,7	2,7	6,0	9,3	18,7
		Space for public use	-	7,2	7,6	2,2	-0,2	-0,7
		Driving lanes	-	5,3	3,4	3,1	3,1	5,3
		Pick-up/drop-off	-	-5,5	-0,8	3,5	3,9	1,6
	Automated ride sharing	Baseline	0,0	5,6	10,4	18,6	36,2	43,1
		Automated ridesharing	-	7,5	11,1	16,5	20,3	20,3
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	5,6	10,4	18,6	36,2	43,1
		GLOSA	-	5,0	3,4	5,0	8,2	8,2
Vehicle occupancy rate	Road use pricing	Baseline	0,0	-4,9	-4,9	3,8	2,0	6,0
		Empty km pricing	-	8,2	8,2	11,6	14,9	16,6
		Static toll	-	10,2	12,0	17,7	15,8	17,7
		Dynamic toll	-	12,9	14,7	21,5	21,5	23,7
	Dedicated lanes for CAVs	Baseline	0,0	0,5	0,6	-3,3	-3,3	0,6
		Dedicated CAV lane (fixed)	-	4,3	3,7	6,3	8,0	10,7
		Dedicated CAV lane (dynamic)	-	3,6	3,6	9,0	9,0	16,9
	Parking price regulation	Baseline	0,0	3,9	-1,7	-1,5	-3,3	-4,6
		Adjusted parking behaviour	-	3,1	3,6	5,7	6,7	13,4
	Replacing on-street parking	Baseline	0,0	-5,7	-5,7	-8,2	-8,7	-9,2
		Space for public use	-	6,8	8,8	8,9	18,9	18,9
		Driving lanes	-	-5,6	-7,6	-3,8	-2,2	-9,7
		Pick-up/drop-off	-	-7,3	-3,3	-2,7	8,9	14,4
	Automated ride sharing	Baseline	0,0	0,2	0,2	-3,9	1,2	10,0
		Automated ridesharing	-	9,4	13,3	19,5	19,5	19,5
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	0,2	0,2	-3,9	1,2	10,0
		GLOSA	-	4,2	4,2	4,2	4,2	4,2

3.3 Impacts on society, road safety and economy

This section presents the estimated impacts of the 6 WP6 SUCs on society, road safety and economy. The indicators used to evaluate the impacts are shown in *Table 3.9*. The methods used to evaluate these impacts are microsimulation, system dynamics and Delphi.

Table 3.9: Society, safety and economy impact definitions

Impact	Definition	Methodology
Vehicle operating cost	Direct outlays for operating a vehicle per kilometre of travel and averaged over all traffic	Delphi
Parking space demand	Required parking space in the city centre per person (m2/person)	System Dynamics / Delphi*
Road safety	Number of predicted crashes per vehicle-kilometre driven (all traffic)	Microsimulation (postprocessing with SSAM + Tarko crash prediction method)
Public health	Subjective rating of public health state, related to transport (10 points Likert scale)	Delphi
Accessibility of transport	The degree to which transport services are used by socially disadvantaged and vulnerable groups including people with disabilities (10 points Likert scale)	Delphi
Average commuting distance	Average length of trips to and from work (added together) in km (all traffic)	System Dynamics

** The Delphi method was also used to estimate a simplified form parking space demand but is excluded from this overview. For Delphi results on parking space demand see Chaudhry et al. (2021).*

The following sections summarise the results from each applied method on society, safety and economy and discuss the estimated effect that these impacts will have if these interventions (SUC) are implemented under the conditions as adopted in LEVITATE.

3.3.1 Road safety: Microsimulation results

Table 3.10 presents the results from each SUC scenario, given different CAV penetration rates, on safety using the microsimulation method. Microsimulation was used to estimate the impact of changing automation levels and the policy intervention sub-use cases on predicted crashes per vehicle kilometre travelled for all passenger vehicles in the network.

The microsimulation software is limited to the simulation of motor vehicles on the road, and therefore does not simulate interactions involving vulnerable road users (VRUs) such as pedestrians and cyclists. As was discussed in Weijermars et al. (2021), increasing penetration levels of CAVs in general is expected to decrease fatalities among VRUs by more than 90% in the case of 100% penetration. For one sub-use case—replacing on-street parking with cycling lanes or public space—a separate estimate for the effect on VRUs was conducted, which can be found in Deliverable 6.4 (Chaudry et al., 2021). Since the exact share of cyclist and pedestrian accidents among VRU accidents can vary strongly between cities, Chaudry et al. (2021) found it difficult to give an exact estimate and assumed a conservative reduction of around 8% of unmotorized VRU at-fault accidents for the removal of on-street parking.

The other sub-use cases in Work Package 6 are not expected to have a large additional effect on specifically vulnerable road users when compared to the baseline scenario. Where larger potential impacts are expected (e.g. ride sharing vehicles stopping for boarding/alighting at undesignated stops, potential effects of a modal shift) it was not feasible to quantify the impacts with the available data and simulation methods. Therefore, impacts on VRUs are not quantified or further discussed for these sub-use cases. Although the road safety estimates do not take into account potential negative impacts such as system failures, cyber criminality and other such impacts, the road safety estimates presented here are considered conservative due to the omission of VRU.

Table 3.910 Estimated impacts of CAVs on safety using the microsimulation method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs (100-0-0).

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (Human-driven vehicle – 1st Generation CAV – 2nd Generation CAV)								
			100-0-0	**80-20-0**	**60-40-0**	**40-40-20**	**20-40-40**	**0-40-60**	**0-20-80**	**0-0-100**	
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%	%	%	**City**
Road safety (crash rate)	Dedicated lanes for CAVs	Baseline	0,0	-7,9	-12,8	-27,4	-47,8	-66,2	-77,5	-87,1	Manchester
		Dedicated lane (fixed)	-	-0,7	-14,6	-27,4	-42,8	-	-	-	
	Parking price regulation	Baseline	0,0	22,0	7,3	-7,4	-31,4	-42,7	-60,3	-66,9	Santander
		Adjusted parking behaviour	-	21,8	2,3	-7,1	-25,4	-30,2	-47,6	-54,6	
	Replacing on-street parking	Baseline	0,0	-14,1	-25,4	-47,0	-59,7	-77,0	-84,3	-91,6	Leicester
		Removing half of spaces	-10,1	-16,7	-32,5	-50,7	-61,9	-79,3	-84,5	-92,6	
		Driving lanes	-14,0	-28,1	-41,8	-55,1	-68,0	-82,5	-88,0	-94,0	
		Pick-up/drop-off points	-2,7	-15,9	-30,6	-49,7	-60,4	-80,3	-85,1	-92,2	
		Public spaces	-17,9	-28,1	-42,2	-57,4	-69,1	-81,4	-88,0	-94,1	
		Cycling lanes	-15,6	-31,1	-43,8	-55,9	-68,5	-81,9	-87,8	-94,4	
	Automated ride sharing (20% of demand)	Baseline	0,0	6,7	-11,6	-32,1	-45,8	-69,0	-76,3	-87,1	Manchester
		20% willing to share	-	-6,0	-11,3	-10,0	-25,2	-50,6	-61,3	-80,1	
		100% willing to share	-	2,6	-7,1	-22,6	-41,5	-60,3	-70,2	-86,8	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	25,7	17,1	24,9	8,1	-48,3	-55,7	-84,5	Manchester
		GLOSA on 3 Intersections	0,0	15,0	6,2	9,6	12,1	-46,6	-56,7	-86,9	

In general, looking at the baseline results, it is clear that regardless of the sub-use case or its scenario, the increasing CAV penetration rate in the vehicle fleet improves road safety by between 55% and 94%. Depending on the simulated network, full penetration of 2nd generation automated vehicles is expected to reduce the crash rate in the **baseline** by 67% to 92%. For the three largest networks analysed (dedicated lanes, replacing on-street parking, and automated ride sharing), baseline reductions of 87% to 92% are predicted.

The impact of the SUCs on road safety is evident when comparing the SUC baseline with the implementation scenario. The strongest positive impact is seen from the **replacing on-street parking** SUC which reveals that all implementation scenarios have a slight additional positive impact on the baseline estimates. This is likely to be caused by reducing the frequency of parking manoeuvres and related congestion, which may be responsible for a small but noticeable number of interactions with a high crash risk. The **parking price regulation** SUC, on the other hand, results in less improvement in road safety than in the baseline scenario. This is possibly due to the increased congestion caused by empty CAVs circulating in the network or driving to park elsewhere while waiting for passengers.

For the **dedicated CAV lane** SUC as well as **GLOSA**, little difference is observed between the SUC scenarios and their respective baselines. Also **automated ride sharing** adds no additional benefits and in fact also has a light negative impact on the baseline development.

3.3.2 Society & economy: System dynamics results

The system dynamics method is used to evaluate two societal impacts as a result of implementing the sub-use case scenarios (*Table 3.11*): demand for parking space, and individual's average commuting distances. The system dynamics model is based on the city of Vienna, Austria, and four of the six sub-use cases are implemented: road use pricing, parking price regulation, replacing on-street parking, and automated ride sharing. These sub-use cases are expected to have more indirect/macroscopic level impacts which can be better captured by the system dynamics model. System dynamics, unlike microsimulation, takes into account the potential indirect influences of a modal shift due to implementation of the SUC measures.

Table 3.1011 Estimated impacts of CAVs on society and economy using the system dynamics method. Percentages indicate the difference relative to the impact's Baseline at 0% penetration of CAVs.

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)						
			0	20	40	60	80	100	
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%	**City**
Parking space demand	Baseline	no policy intervention	0,0	2,7	8,0	19,7	34,7	47,3	Vienna
	Road use pricing	Static toll: 10 euros	-34,2	-32,9	-31,6	-30,8	-30,1	-28,0	
	Parking price regulation	Adjusted parking behaviour	-28,1	-28,7	-28,2	-28,1	-26,6	-27,1	
	Replacing on-street parking	Removing half of spaces	-22,2	-17,3	-8,0	14,9	34,2	47,3	
		Driving lanes	-20,5	-15,6	-2,0	25,3	44,8	57,3	
	Automated ride sharing	20% of demand & 100% willing to share	0,0	2,7	7,8	19,3	34,4	46,8	
Average commuting distances	Baseline	no policy intervention	0,0	0,0	0,0	0,0	0,0	1,0	
	Road use pricing	Static toll: 10 euros	0,0	0,0	0,0	0,0	0,0	1,0	
	Parking price regulation	Adjusted parking behaviour	0,0	0,0	0,0	0,0	0,0	1,0	
	Replacing on-street parking	Removing half of spaces	0,0	0,0	0,0	0,0	0,0	1,0	
		Driving lanes	0,0	0,0	0,0	0,0	0,0	1,0	
	Automated ride sharing	20% of demand & 100% willing to share	0,1	0,1	0,2	0,3	0,5	1,0	

Parking space demand

The system dynamics methodology predicts that parking space demand without any interventions (**baseline**) will increase by up to 47% once all vehicles are CAVs. This is driven by the fact that the system dynamics model predicts a modal shift towards private vehicle transport with increasing automation. The increases are indicated in red since the increase in parking space demand places an additional financial/spatial burden on cities with limited available space.

The introduction of **road use pricing** and **parking price regulation** interventions is estimated to significantly reduce the demand for parking space, particularly when the share of CAVs is low (up to 33% reduction compared to 0% CAV) but also once full CAV penetration is reached (up to a 28% reduction compared to 0% CAV and a massive swing of around 73% compared to the baseline with 100% CAV). Even as the demand for parking slightly increases with increasing automation, with implementation of road use pricing or parking price regulation, this increase is substantially less than in the baseline trend. These results largely reflect a predicted mode shift away from private car use to active modes and public transport due to the increased costs (in terms of tolls and time) of using a private vehicle in the city centre with these policy measures.

In both scenarios of **replacing on-street parking,** removing half of the spaces or replacing all spaces with driving lanes, the demand for parking is greatly reduced when CAV penetration is low. However, this effect is negated, and the measure has no added effect (or in the case of adding driving lanes, demand increases even more) once the penetration of CAVs reaches 60% or higher. **Automated ride sharing** has no added impact compared to the baseline trend.

Average commuting distance

In general, average commuting distance in the **baseline** is estimated to only increase by 1% when the CAV penetration rate is at 100%. Implementation of the **SUCs** have no meaningful added effect compared to the baseline estimate.

3.3.3 Society & economy: Delphi results

The Delphi method was used to estimate the effects of the six WP6 sub-use cases on three additional societal/economic impacts: vehicle operating cost (VOC), public health, and equal accessibility to transport. The expected effects of CAV introduction and associated SUC interventions on these societal and economic indicators are shown in *Table 3.12*.

As mentioned earlier (e.g. 3.2.4), the baseline values for each SUC differ because a different group of experts was asked for each SUC. For more information, see Appendix A.

Table 3.1112 Estimated impacts of CAVs on society and economy using the Delphi method. Percentages indicate the difference relative to the SUC's Baseline at 0% penetration of CAVs.

			Deployment scenarios: Market penetration rate **of CAVs** in **entire** vehicle fleet (percentage share of CAVs)					
			0	20	40	60	80	100
Impact	**Sub-use case**	**Scenario**	%	%	%	%	%	%
Vehicle operating cost	Road use pricing	Baseline	0,0	6,1	4,2	4,3	-5,5	-7,4
		Empty km pricing	-	2,3	2,3	2,5	-3,1	-3,1
		Static toll	-	19,9	19,4	15,4	9,3	9,3
		Dynamic toll	-	17,3	15,3	14,9	12,8	13,3
	Dedicated lanes for CAVs	Baseline	0,0	11,7	11,7	4,8	4,3	0,2
		Dedicated CAV lane (fixed)	-	4,9	1,6	-4,3	-9,4	-11,4
		Dedicated CAV lane (dynamic)	-	-5,6	-5,6	-5,6	-14,0	-18,5
	Parking price regulation	Baseline	0,0	12,9	9,0	-1,0	-10,1	-19,7
		Adjusted parking behaviour	-	8,0	8,7	11,9	12,0	13,5
	Replacing on-street parking	Baseline	0,0	-8,6	0,5	8,4	16,4	12,8
		Space for public use	-	0,6	-5,0	-1,5	-2,8	-0,7
		Driving lanes	-	12,7	12,8	13,8	18,4	13,8

		Pick-up/drop-off	-	0,3	-0,3	6,2	3,8	10,7
	Automated ride sharing	Baseline	0,0	14,5	12,3	12,4	9,5	8,5
		Automated ridesharing	-	4,3	4,2	-9,6	-15,7	-20,1
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	14,5	12,3	12,4	9,5	8,5
		GLOSA	-	-3,2	0,4	2,8	2,8	2,8
Public health	Road use pricing	Baseline	0,0	2,1	3,8	7,4	7,4	11,8
		Empty km pricing	-	7,7	7,7	5,7	9,6	9,6
		Static toll	-	10,8	14,3	10,8	9,0	9,0
		Dynamic toll	-	11,1	11,1	9,0	5,4	7,1
	Dedicated lanes for CAVs	Baseline	0,0	-5,7	-5,7	-5,8	-6,2	-11,2
		Dedicated CAV lane (fixed)	-	-1,5	-3,8	0,8	-1,6	5,1
		Dedicated CAV lane (dynamic)	-	-0,4	-3,8	3,0	3,1	4,8
	Parking price regulation	Baseline	0,0	3,6	1,8	5,5	5,6	8,0
		Adjusted parking behaviour	-	-2,0	-3,0	-2,9	-4,0	-2,5
	Replacing on-street parking	Baseline	0,0	0,3	2,3	6,8	9,8	10,3
		Space for public use	-	10,7	18,8	23,9	33,5	44,5
		Driving lanes	-	-3,7	-8,2	-20,1	-16,1	-32,1
		Pick-up/drop-off	-	2,2	2,2	8,3	10,4	12,9
	Automated ride sharing	Baseline	0,0	2,5	4,5	7,0	7,0	7,0
		Automated ridesharing	-	4,4	4,9	8,8	8,8	8,8
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	2,5	4,5	7,0	7,0	7,0
		GLOSA	-	0,2	0,2	0,2	0,2	0,2
Equal accessibility of transport	Road use pricing	Baseline	0,0	-0,7	5,4	8,5	13,1	14,6
		Empty km pricing	-	-3,8	-3,8	-3,7	-1,1	-2,6
		Static toll	-	-8,2	-5,2	-4,0	-1,0	2,0
		Dynamic toll	-	-5,7	-5,7	-5,7	-4,2	-5,7
	Dedicated lanes for CAVs	Baseline	0,0	4,2	4,2	4,2	6,3	6,3
		Dedicated CAV lane (fixed)	-	0,2	-1,5	3,0	-3,8	0,3
		Dedicated CAV lane (dynamic)	-	0,2	-3,2	5,4	0,3	3,7
	Parking price regulation	Baseline	0,0	3,9	5,8	11,5	16,3	24,8
		Adjusted parking behaviour	-	2,0	2,0	3,9	5,3	4,4
	Replacing on-street parking	Baseline	0,0	-1,3	-0,8	0,7	7,7	12,7
		Space for public use	-	-3,7	-9,7	-12,1	-10,1	-13,1
		Driving lanes	-	0,3	4,8	10,8	10,9	20,9
		Pick-up/drop-off	-	-1,7	0,3	6,8	9,3	9,8
	Automated ride sharing	Baseline	0,0	9,1	9,1	12,9	18,7	17,1
		Automated ridesharing	-	9,1	13,7	18,6	17,1	13,8
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0	9,1	9,1	12,9	18,7	17,1
		GLOSA	-	5,0	5,0	5,0	5,0	5,0

Vehicle operating cost

For vehicle operating cost (VOC), expected developments in the **baseline** scenarios vary greatly depending on the expert group consulted for each SUC. In four of the baselines (dedicated CAV lanes, replacing on-street parking, automated ride sharing, and GLOSA) the VOC is expected to increase at most, or all CAV penetration rates. The baseline of the replacing on-street parking SUC is estimated to initially (up to 20% CAV penetration levels) decrease VOC whereafter the VOC are estimated to increase by nearly 13%. For two of the baselines (road use pricing and parking price regulation), the VOC is expected to first increase and then decrease as CAV penetration rates pass 60%. Overall, the experts mostly expect vehicle operating costs to increase especially at low penetration rates; once CAVs reach higher penetration levels, the expectations for the effects on VOC are mixed.

Regarding the effects of the SUC interventions, experts estimate that both static and dynamic toll **road use pricing** will increase vehicle operating costs over the baseline estimates. Empty kilometre pricing will initially reduce VOC over the baseline but as penetration rates increase the intervention will negate some of the benefits caused by CAV introduction (the reductions are less than in the baseline).

Implementing **dedicated lanes for CAVs** is expected to reduce vehicle operating costs as penetration of CAVs increases. This is especially true for the dynamically controlled dedicated lanes.

For **parking price regulation**, the "adjusted parking behaviour" scenario increases the estimates of VOC by up to 13,5% (compared to baseline 0% CAV). Especially the "return to origin" and "drive around" behaviours, as an alternative to parking at the destination, are expected to increase vehicle operating costs (see Appendix D).

Furthermore, for the **replacing on-street parking** SUC, experts estimate that reserving "space for public use" will reduce VOC estimates compared to the baseline once CAV penetration rates increase to above 20%. Replacing on-street parking with "pick-up/drop-off" spaces for shared vehicles is also, to a lesser degree, expected to lead to less increase in VOC than in the baseline at higher penetration rates. Replacing on-street parking with extra "driving lanes" on the other hand, is expected to slightly increase VOC above baseline estimates.

Both the **automated ride sharing** and **GLOSA** SUCs were estimated by experts to reduce VOC compared to the baseline estimates. For automated ride sharing, reductions of as much as 20% were predicted compared to baseline 0% CAV.

Public health
Looking at the effects on public health, experts estimate that the introduction of CAVs in most of the **baseline** scenarios will have a positive impact on public health, with improvements of 7-12% at full CAV penetration. The exception to this positive outlook is the baseline estimated in the dedicated lanes SUC survey, which predicts that transport's impact on public health will worsen by roughly 11% at full CAV penetration.

Regarding the impacts of the SUC implementation, three of the SUCs result in reduced positive effects on public health compared to their respective baselines: **road use pricing**, **parking price regulation**, and **GLOSA**. Of these three SUCs, the largest negative effect on public health is expected for parking price regulation, which is especially true for the "drive around" alternative to normal parking behaviour (see Appendix D). For road use pricing and GLOSA, the effects are less positive than in the baseline but still show slight positive (road use pricing) or neutral (GLOSA) development compared to the starting point with 0% CAV penetration.

The **dedicated lanes for CAVs** and **automated ride sharing** SUCs are estimated to have added benefits for public health over those in the baseline. For **replacing on-street parking**, expectations vary greatly depending on what facilities replace the on-street parking spaces. Large positive impacts were estimated for replacing on-street parking with "space for public use" up to 45% compared to the baseline starting point with no CAVs, an increase of 35% more than in the baseline. On the other hand, replacing the parking spaces with "driving lanes," is expected to have a large negative development in public health of -32% compared to the baseline.

Equal accessibility of transport

The final impact evaluated is on equal accessibility of transport to all users. In this instance, all expert groups estimated that the introduction of CAVs would positively impact accessibility for all **baseline** developments. Depending on the survey, experts predicted an improvement of between 6% and 25% in accessibility when the entire vehicle fleet is automated.

However, with the exception of replacing on street parking with driving lanes, all SUC interventions are predicted to negate a significant portion of the benefits estimated in the baseline. When compared to the baseline, **road use pricing** is estimated to negatively impact equal accessibility, especially for a dynamically controlled toll. The **dedicated lane for CAVs** and **parking price regulation** SUCs are also expected to reduce the benefits to accessibility expected in the baseline. For parking price regulation, the changed parking behaviour has a major negative impact on the baseline estimate for equal accessibility, reducing it from 24% to 4%.

The expected effects of **replacing on-street parking** again depend highly on which facilities replace the parking space. Replacing the on-street parking with "space for public use" is expected to reduce accessibility by 13% compared to the baseline. Meanwhile, replacing on-street parking with "driving lanes" is expected to significantly increase accessibility by 21%. Replacing parking with "pick-up/drop-off" spaces shows a similar, but slightly reduced, effect on accessibility compared to the baseline.

The last two sub-use cases of **automated ride sharing** (14%), and **GLOSA** (5%) both improve equal accessibility of transport when CAV penetration rate is at 100% compared to the starting point, but the effect is lower than the baseline scenario (17%) suggesting that these SUCs partially negate the positive effect of increased CAV penetration.

4 Discussion

This chapter discusses the main findings/conclusions about the expected impacts after introducing the sub-use case scenarios. The strengths and limitations of the theoretical and empirical work underlying these impacts are discussed, and related policy considerations are presented.

4.1 Main findings

The main findings from the work done in WP6 as discussed in Chapter 3 (and Appendix D) relate the effect that introducing CAVs will have on the environment, mobility, road safety, society and economy, also known as the baseline effect. These effects are estimated by applying (combinations of) four different methods. Furthermore, the effect of six policy interventions (or SUCs) on a number of indicators (or impacts) is estimated and compared to the baseline effect. In this chapter we summarise and discuss these results. Also, a further look is taken at how some findings are similar or different depending on the research method adopted.

Baseline developments

The increasing penetration levels of connected and automated vehicles (CAVs) in the urban city area is estimated (for most baselines) to have a positive impact on the **environment** (less emissions, higher energy efficiency), on **society, safety & economy** (improved road safety, public health, and lower vehicle operating costs) and on most **mobility** indicators (more access to travel and less congestion). In the absence of policy interventions, some potentially negative effects could be realised if private automated vehicle transport leads to a decline in walking, cycling, and/or public transport trips.

The impacts for the various SUC are measured relative to the baseline starting point: the situation with no intervention or presence of automated passenger cars. Important to note is that baseline estimated vary across methods and the city networks to which CAVs and the SUCs were applied. In the microsimulation, results for the baseline estimates differ between SUCs due to different networks being studied for each SUC. For the mesosimulation and system dynamics impacts, one baseline was calculated for the entire city of Vienna, which may also show different effects from the networks used in the microsimulation. Also, the baseline estimates in the Delphi method differ across SUCs because different expert groups evaluated different SUCs. The results therefore reflect the implementation of CAVs under a wide range of conditions, networks, and methodologies. The results serve as indicative of impact ranges rather than definitive estimates, which would have required a much larger study as well as more observational data which is unavailable due to the early stages of automated technology. Care must be taken in generalising the results to situations to those which are comparable to those modelled in Levitate. The results are transferable in as far as they are applied to networks that are comparable to those used in Levitate (Haouari et al., 2021; Sha et al., 2021; Chaudhry et al., 2021).

The following points summarise the primary baseline results:

- Environment: For the **CO_2-emissions**, in all five sub-use case networks a substantial positive baseline development was estimated, even at low levels of CAV penetration (CO_2 emissions reduction of 20% at 20% CAV penetration rate). This is due to the assumption that all CAVs are electric vehicles. Out of the six estimated baseline scenarios for the development of **energy efficiency**, all expert groups predicted that energy efficiency will improve once CAV penetration exceeds 60% (5% to 31% improvement at full penetration). For two of these baseline estimates, a slight initial decrease in energy efficiency is predicted at low CAV penetration rates.
- Mobility: For the mobility domain, on the positive side most (4 out of 5) baselines predict a reduction of **congestion** (between 9% and 13% reduction), most predict an increase in **shared mobility rates** (between 11% and 41% increase at 100% CAV penetration level), and most baselines predict an increase in the **vehicle utilisation rate** (four out of the six baselines estimate an increase between 43% and 50% increase at 100% CAV penetration level). However, on the negative side, most baselines in both the Delphi study and system dynamics model predict a reduction in the **modal split of active transportation** (between 13% and 56% reduction at 100% CAV penetration level) and **public transport** (between 10% and 29% reduction at full automation) in favour of CAVs. For **total kilometres travelled, travel time** and **vehicle occupancy rates,** different baselines produce very different results; there seems to be no clear pattern for these impacts.
- Road safety: Regarding **safety**, for all the baseline networks, a substantial improvement in road safety is predicted at full penetration of automated vehicles (67% to 92% reduction in the rate of crashes between passenger vehicles). At lower penetration rates when there is still mixed traffic on the road, the impact on crash rates is more gradual. For three out of the five baselines, an improvement in road safety is already clear with the presence of 40% CAVs on the road (11% to 25% reduction in crash rate). For the other two baseline networks (Santander and the GLOSA network from Manchester), a temporary increase in crash rates is predicted in low penetration rates when many human-driven vehicles are still on the road. This is likely due to interactions between human-driven vehicles and CAVs, whose different driving styles may cause some additional conflicts. Once human-driven vehicles are no longer on the road, all baselines show a large decrease.
- Society/Economy: Most baselines (5 out of 6) predict an improvement in **public health** (2% to 12% improvement), and all 6 baselines predict an improvement in **equal accessibility of transport** (mostly between 4% and 25%). Effects on **vehicle operating costs** are mixed as CAV penetration increases to 100% (-20% to +13%), but at lower penetrations (20% to 40% CAVs) all baselines predict vehicle operating costs to at least temporarily increase. The results for **parking space demand** estimated by system dynamics predict parking space demand to increase as CAVs become more widespread. This is due to a predicted mode shift towards private automated vehicle travel from other modes (e.g. public transport), thus increasing the demand for parking if no further policy measures are taken.

The effect of the SUC interventions
Below is a summary of the findings from the six major sub-use cases and their implementation scenarios:

1. Road use pricing**:** Road use pricing is expected to lead to a number of additional benefits over the baseline impacts: better **energy efficiency** (dynamic toll more than static toll or empty km pricing), less reduction in the use of **active modes** and **public transport**, higher **vehicle occupancy** rate, and lower **parking space demand**. On the negative side, road use pricing is expected to lead to increase in **vehicle operating costs**, and

less equal accessibility of transport. The scenario "empty km pricing" is expected to contribute more positively towards keeping vehicle operating costs within bounds compared to the "static toll" and "dynamic toll" scenarios. The "static toll" scenario is expected to result in the highest shares in active transport modes and public transport. The "dynamic toll" scenario is expected to lead to the highest vehicle occupancy rates.

2. Dedicated CAV lanes: Compared to the baseline, dedicated lanes for CAVs do not make a clear difference for emissions, travel time, kilometres travelled, and road safety. On the positive side, dedicated lanes are expected to lead to better **access to travel** when lanes are "dynamic," slightly reduced **congestion** in mixed human-driven/CAV traffic, a higher **vehicle utilisation** rate, higher **vehicle occupancy** rate, and lower **vehicle operating costs**. The "dynamic" lanes scenario performs better than the "fixed" lane scenarios in terms of improvements on energy efficiency, access to travel, vehicle occupancy rate, vehicle operating costs, and in terms of a lesser decrease of the active mode share.

3. Parking price regulation: Parking price regulation does not seem to make a noticeable difference on CO_2 emissions or shared mobility rate. On the positive side, parking price regulation is expected to compensate some of the negative impacts of CAVs on the **mode share of public transport** and **active modes**, resulting in more walking, cycling and public transport use than in the baseline development. However, in both cases these interventions cannot overcompensate for the negative impact that CAVs are expected to cause to the modal share of public transport and active modes. Less private vehicle use than in the baseline also results in a reduced demand for **parking space**, according to the system dynamics model. The alternative parking behaviours resulting from parking price regulation are predicted to have some potentially negative (or less positive) effects compared to the baseline development on **energy efficiency**, **travel time** and **congestion**, and **road safety**. However, these negative effects predicted by microsimulation and Delphi do not take into account the effects on modal split predicted by system dynamics which may counteract these effects to a certain degree if private vehicle transport is reduced. Reduced benefits are also predicted for **access to travel**, **equal accessibility of transport**, **vehicle utilisation rate**, and **vehicle operating costs**, due to the increased costs of parking in central locations.

4. Replacing on-street parking: The interventions aimed at **replacing on-street parking** show similar results to the baseline (no added effect) in terms of CO_2 emissions. Positive effects on mobility in terms of reduced **travel time** and **congestion** are predicted due to the reduction in parking manoeuvres. For many of the impacts, the effect of replacing on-street parking was dependent on the scenario: removing half of spaces, replacing with driving lanes, replacing with pick-up/drop-off spaces for shared CAVs, or replacing with public space or cycling lanes. Replacing with "public space" was found to be particularly beneficial for **energy efficiency**, **shared mobility rate**, **modal splits of active** and **public transport**, **vehicle occupancy rate**, **vehicle operating cost**, **road safety**, and **public health**, but negative in terms of **access to travel.** Meanwhile, replacing on-street parking with "driving lanes" is expected to improve **access to travel** and use of **active modes** (to a lesser degree than public space), but reduce the mode share of **public transport** and negatively impact **public health** and **parking space demand**. The scenario "pick-up/drop-off" generally performs worse than the other scenarios in terms of **energy efficiency, travel time**, **kilometres travelled, congestion**, shares of **active transport modes** and **public transport**, **shared mobility rate**, and **road safety**. On the positive side, the "pick-up/drop-off" scenario

is expected to result in better results for **access to travel** and **equal accessibility of transport** than the other scenarios in the replacing on-street parking SUC.

5. Automated ride sharing: Automated ride sharing does not make a noticeable difference for CO_2 emissions or parking space demand. Compared to the baseline, extra benefits are expected in terms of **energy efficiency**, **access to travel**, **public transport use**, **shared mobility rate** (at lower CAV penetrations), **vehicle occupancy rate**, and **vehicle operating costs**. Compared to the baseline, it has a negative impact on **congestion** (due to empty vehicle kilometres needed to reposition vehicles), **travel time**, use of **active modes**, and **vehicle utilisation rate**. The impact on **road safety** is mixed: at low CAV penetrations, automated ride sharing improves safety by serving a share of otherwise human-driven trips. However, as all trips become automated the added benefit reduces and the extra congestion caused by ride sharing rather serves to slightly increase crash rates compared to the baseline at high penetration rates. Furthermore, the impacts of automated ride sharing depend on what share of the users are willing to share trips with other users. When willingness to share is low (20% scenario), fewer positive results are predicted for mobility and road safety due to the larger number of trips and vehicles needed to serve the demand (travel time and congestion increase; kilometres travelled and road safety decrease).

6. GLOSA: The **GLOSA** sub-use case is associated with no noticeable additional impacts on CO_2 emissions or kilometres travelled. Compared to the baseline it shows positive impacts on **travel time**, **congestion**, **public transport use**, **road safety**, and **vehicle operating costs**. A negative (or less positive) impact compared to the baseline is predicted for **access to travel**, **active mode share**, **shared mobility rate**, **vehicle utilisation rate**, **public health**, and **equal accessibility of transport**.

4.2 Strengths and Limitations

Like most projects of this type, LEVITATE has strengths and limitations. A potential strength of the LEVITATE project is that both smart city transport policy interventions and the associated impacts have been selected by a diverse group of stakeholders. A wide variety of impacts were studied at the same time and the project tried to capture interdependencies. The best available methods, microsimulation, mesosimulation, Delphi, and other complementary methods such as system dynamics and operations research, were used to study and quantify the expected impacts of mobility interventions intended to support CAV deployment and sustainable city goals. These impacts provide essential input for developing a practical Policy Support Tool for city policy makers. Above all, the knowledge from LEVITATE is intended to contribute and support future policy development and policy-making for smart city transport and traffic.

However, we also recognize that LEVITATE has limitations. Firstly, we discuss some general limitations or difficulties concerning predicting future trends and, secondly some limitations that are more specifically related to the specific methods used in deriving the estimates.

Limitations in predicting future trends

Research evidence is not available for all potential impacts of connected and automated vehicles identified in LEVITATE. Specific potential impacts of CAV that are difficult to predict with any confidence are the following (Elvik et al., 2020; Bin, 2021[1]):

- Whether there will be a widespread transition from individual to shared mobility. There is no consensus on whether individual use of motor vehicles will continue at present levels or will be replaced by various forms of shared mobility. This will largely be impacted by the policy measures of the city and national authorities. Therefore, the LEVITATE project aims to support the authorities finding the most beneficial policies on the way towards an automated transport system.
- It is not clear what type of propulsion energy connected and automated vehicles will use. Some researchers expect the introduction of connected and automated vehicles to be associated with a transition to electric propulsion. In LEVITATE project the assumption has been made that all CAVs are electric vehicles. This raises additional important questions including whether the electric power grid is able to keep up with the demand of the CAV/EVs, and whether the electric energy comes from a sustainable source. These aspects fall beyond the immediate scope of LEVITATE and have not been considered.
- Connected and automated vehicles are vulnerable to cyber-attacks. However, the risk of such attacks cannot be quantified. Only potential scenarios can be described. This is an aspect which has not been explicitly considered in the impact estimations (Elvik et al., 2020).
- The costs of operating CAVs are highly uncertain. It is not clear whether CAVs will be as affordable as current motor vehicles. However, there is a broad consensus that a significant cost reduction in urban transport will be realized when human drivers are no longer required to operate road-based vehicles.
- Behavioural adaptation to connected and automated vehicles, in particular during the transition period before full market penetration, remains uncertain. While some studies suggest various forms of behavioural adaptation, predicting its form and impacts is impossible and highly speculative.
- Changes in employment are difficult to predict. While full automation will eliminate the need for drivers, other potential impacts affecting changes in employment are less known and have therefore been excluded as an impact in Levitate.

Specific method-related limitations

There are some remarks to be made about the possible limitations or nuances of the methodologies used within LEVITATE for WP6:

- The Delphi method made use of different groups of experts for each SUC. This resulted in some discrepancy in the baseline estimates of the different impacts within one SUC. Using one group of experts for all the (6) sub-use cases may have led to other outcomes. However, since this method strives for consensus within groups through an iterative process of scoring and assessing, it is likely that the outcomes of a second group of experts assessing the same 6 SUCs would have also deviated from the first. This method is dependent on the individuals who are considered to be experts; even experts are known to have different opinions so variations in outcomes are inherent to the method.
- The results of the microsimulation models are dependent upon assumptions underpinning the parameters (see Chaudry et al., 2021). Where possible, these assumptions are based on previous research; however, due to the unavailability of real-

1. Personal communication with Hu Bin from AIT

world data, proven parameters are not always available. Applying a different set of assumptions may lead to other outcomes.

- Microsimulation network size: Especially for the Santander network used to estimate the impacts of parking price regulation, the small size of the network led to high variability between simulation runs (see Appendix C) and therefore a higher level of uncertainty than for the other networks (especially Manchester).
- Comparability & transferability: Each quantitative simulation method has different parameters and is applied to a different city model. For example, the mesoscopic simulation uses the MATSim model for Vienna and the microscopic simulation considers the AIMSUN model for Manchester, Leicester and Santander; therefore, the results cannot be immediately generalized. Within Work Packages 5 and 7, results have also been calculated for the cities of Athens and Vienna. Results are most transferable to those urban conglomerates which have structural and dynamic characteristics that are similar to those of the city networks modelled in LEVITATE.
- Driving profiles: The simulation models used examined only two CAV driving profiles (aggressive vs. cautious) to represent development of automation technology; future work may extend the number of profiles.
- Simulation of pedestrians and cyclists was not possible in the microsimulation model.

4.3 Policy considerations and discussion

The SUCs or policy interventions studied in the LEVITATE project are part of a wider transition to smart mobility and smart cities. In this section we will reflect on a number of relevant broader policy issues surrounding the introduction of Cooperative, Connected and Automated Mobility (CCAM) in urban areas.

Planning and governance of automated mobility in urban environments
Implementing new forms of CCAM is a highly complex process, particularly in the urban environment. Many different actors in city governance, industry and the general population will need to come together to deal with these challenges. Although there may be a strong push from industry to implement new smart mobility services, there are still many uncertainties that lie beyond the powers or competence of any one single actor to fully control or address. Adequate legislation and technical standards are expected to lag behind CAV deployment trials and pilots (in other words, technology develops faster and legislation and standards etc. have to follow). It is important to anticipate these developments and to start the processes necessary for adopting standards and legislation that will be necessary to regulate large scale CCAM deployment. An example we can learn from is the advent of the motor car in a largely unregulated transport environment and which introduced many negative impacts which in time, and to this day, need mitigation. The Safe Systems method is about prevention, and this pleads for a pro-active approach, also with respect to standards, legislation and regulation.

There is enthusiasm about the transition towards smart mobility, but not surprisingly opinions vary. Fraedrich et al. (2019) carried out a survey among city planners in 24 German cities. Half of the respondents believed that shared autonomous vehicles could positively contribute to urban planning objectives, but only 10% reported that private autonomous cars could contribute to those objectives. According to the respondents, implementation of automated vehicles would require preparatory action in the fields of transportation planning, traffic control, road infrastructure, urban planning, citizen participation, test fields and data standards and requirements. Additional interviews with city planning experts led to four major insights namely

- Cities themselves are a major driving force
- for city renewal or redevelopment, public transport is a major goal
- there is concern about the possibility of an increase of private car use in cities
- city goals are not always directly aligned with other stakeholders seeking to push automated vehicle technology

In the USA, McAslan et al. (2021) have looked at plans for autonomous vehicles amongst Metropolitan Planning Organizations (MPOs). One key area that requires attention is public engagement in the management of emerging technologies. This element seems critical to advancing CAVs in a way that addresses issues of equity and mobility justice (and others). Equity, accessibility, and other similar public health goals are often promoted by industry, but ultimately the realization of these is ultimately a policy decision (McAslan et al., 2021). Several of the studied Regional Transportation Plans did have policies to address equity and accessibility. However, MPOs need to engage stakeholders, both from the public sector and industry, to ensure that public health goals like equity, accessibility etc. are prioritised in addition to safety and mobility goals in the transportation decision making process. Left to market forces alone, it is likely that these potential benefits will not be realised and could even worsen (McAslan et al., 2021).

Many authors have stressed that the industry and economy forces that tend to push towards implementation of automated driving, should be balanced by an equally strong orientation on the social-ethical (or the non-technical) dimension of the new technology. In other words, how it is governed, how it is perceived by citizens from various social strata, whether it complies with ethical guidelines and whether it really provides the expected benefits for the city (Fraedrich, 2019; McAslan et al, 2021; Habibzadeh et al, 2019, Milakis & Muller, 2021). In recognition of this, authors have suggested that new types of national, local or city governance (or management) are needed to steer the transition towards automated mobility in a responsible way (e.g., Aoyama & Leon, 2021; McAslan et al., 2021; Milakis & Muller, 2021).

Milakis & Muller (2021) suggest that policy makers need new tools for long term planning to accommodate uncertain urban futures. They argue in favour of new participative anticipatory governance instead of traditional governance which is typically supported by forward looking exploratory deployment scenarios with short term implications. They suggest a research agenda that is more oriented on citizens than consumers, more focused on long term than only short term and more based on citizen participation than traditional short-sighted scenario analysis. Their emphasis on normative scenario analysis (i.e., back casting) aligns well with the LEVITATE project.

McAslan et al. (2021) argue for anticipatory governance looking at future scenarios, using flexible planning mechanisms, and where monitoring and learning are built in the planning process, and the public is actively engaged.

Aoyama & Leon (2021) conclude that cities are part of multi-scalar governance frameworks where new rules, regulations, strategies, and standards are negotiated and enacted. They identified four key roles for cities in the governance of the emerging autonomous vehicle economy: regulator, promoter, mediator, and data catalyst. They cite the example of the city of Pittsburgh which, in recent years, has shifted away from a role of being promotor to a new role of being mediator. The initial emphasis of the city government on the promotion of the autonomous vehicle economy has decreased and has given way to an acknowledgment of the need to build more equitable relationships between various stakeholders in the city area. Another example of a city taking up a different governance role is Boston. In recent years, Boston's city government has become very active as a data catalyst; the city takes an active approach in exploring partnerships on data collection and developing a shared research agenda that includes not only vehicle testing, but also business model exploration, experiments with connected transportation infrastructure, and research on autonomous mobility and its implications on Boston's workforce.

Planning for future urban city mobility: four types of readiness

On the city level, policy makers and planners face four major areas where preparation is needed to enable future use of CAVs (Alawadhi et al., 2020).

1. the road infrastructure needs to be adapted in order to facilitate proper functioning of automated vehicle systems.
2. the digital infrastructure needs to be set in place, including a framework, technical standards and procedures for cybersecurity and data privacy.
3. there needs to be clarity about how legal responsibilities and liabilities may be solved and how problems in this area may be avoided.
4. the social understanding, acceptance and approval of the new forms of mobility amongst various citizen groups and stakeholders in the urban area seems critical.

Legal readiness

The EU has not yet amended its legal framework to incorporate AV-related liability and insurance risks, but it is exploring solutions to these issues. In 2016 the European Commission launched GEAR 2030 in order to explore solutions to AV-related liability issues. In May 2016 European Parliament Members recommended that the EC should create a mandatory insurance scheme and an accompanying fund to safeguard full compensation for victims of AV accidents and a legal status should be created for all robots to determine liability in accidents (Taeihagh & Lim, 2019).

Looking at recent developments in the five major areas for legal reform the following conclusions can be drawn:

- *Admission and testing:* various countries and states have applied different legal rules for admission and testing of automated vehicles[2]; in the future comparative review of these regulations and associated experiences and outcomes should lay the groundwork for a more uniform approach in the EU and internationally (Lee & Hess, 2020)
- *Liability:* the possible theoretical and legal solutions to liability and insurance have been outlined by various authors (Evas, 2018; Mardirossian 2020; Bertolini & Ricaboni, 2021; Vellinga, 2019) and further discussion between stakeholders and the development of specific cases of litigation will determine the legal option that is chosen
- *Human-machine interaction*: in this particular area a lot of research is still needed to answer questions on which design of the human-machine interface will allow safe and reliable control of the vehicle, in all possible circumstances and involving different traffic situations and different internal states of the driver. Uniform standards can only be formulated once this research has been carried out and main

2. Published/collected on websites like: https://globalavindex.thedriverlesscommute.com/; https://www.ncsl.org/research/transportation/autonomous-vehicles-legislative-database.aspx

conclusions have been agreed upon by all stakeholders involved (Kyriakidis et al., 2017; Morales-Alvarez et al., 2020; Carsten & Martens, 2019)

- *Road infrastructure:* both within EU and USA work has been done to formulate general definitions of the new road classes that are needed to support automated and autonomous vehicles (Rendant & Geelen, 2020; Liu et al., 2019; Saeed et al., 2020). In the Inframix project, so-called ISAD levels (Infrastructure Support Levels for Automated Driving) were developed in which an impetus is given to define the minimum infrastructure (physical and digital) required to enable certain self-driving functions (Rendant & Geelen, 2020); for conventional road infrastructure recognition of road geometry and signs is important and maintenance is crucial for this; as yet there are no norm or standards in EU referring to traffic sign machine readability (Lytrivis et al., 2019) .
- *Digital infrastructure:* connected cars require that every vehicle's location and journey history be recorded and saved, but the current level of IT security cannot prevent yet that data may be accessed by unwanted third parties. Thus, the development of cybersecurity is of the utmost importance for the development of connected and autonomous driving (Medina et al., 2017). At the moment the automotive industry lacks a standard approach for dealing with cybersecurity (Burkacky et al., 2020). The EU, through the European Union Agency for Network and Information Security (ENISA) had proposed good practices that should be considered (Medina et al., 2017).
- *Specific issues concerning electric vehicles*: The costs of battery technology, the number of charging stations and the charging wait time are main variables that will influence electrification of vehicle fleet (Mahdavian et al., 2021). It has been estimated that converting all passenger cars in USA to electric vehicles would consume 28% more power than the US currently produces (Mahdavian et al., 2021).

Road infrastructure readiness

Road infrastructures will have to be adapted in order to be ready, readable, and cooperative in all situations and weather conditions (Gruyer, 2021). CAVs require highly visible road edges, curves, speed limit and other signage (Liu et al.,2019). For the EU it is important to have uniform road markings. The roadside digital infrastructure needs to meet various connectivity requirements.

The lack of sufficiently visible road markings is at the moment an obstacle for some manufacturers for the reliable functioning of autonomous vehicles (Rendant & Geelen, 2020). The reliability of systems such as ISA and LDWA, are dependent on legible road markings for reliable functioning (Korse et al., 2003; Eurorap, 2013). Other infrastructural aspects have to do with harmonisation of the road infrastructure (colour, reflective materials, etc.). In Europe this will likely have a positive influence on the roll-out of CAVs (Rendant & Geelen, 2020). The development of camera technology and image processing algorithms is so fast that future systems will likely be able to deal with lower quality markings. Upgrading road markings to support self-driving vehicles may not be necessary (Rendant & Geelen, 2020).

In the Inframix project, so-called ISAD levels ("Infrastructure Support Levels for Automated Driving") were developed in which an impetus is given to define the minimum infrastructure (physical and digital) required to enable certain self-driving functions. Such an approach makes sense to clarify what level of automation is possible on a given road section (Rendant & Geelen, 2020)

Readiness to address cybersecurity and data privacy concerns

The successful operation of CAVs and their expected impact depend significantly on their management (as part of the greater traffic network and as data carriers and providers) and addressing risks associated with them (Lim & Taeihagh, 2018). Two of these risks are privacy and cybersecurity. The ability of CAVs to store and communicate personal data may conflict with data privacy laws. Cybersecurity is at stake when communication networks crucial for safe operation of CAVs can be hacked. Lim & Taeihagh (2018) conclude that within the EU a proper implementation of the General Data Protection Regulation (GDPR) can ensure privacy protection. These researchers argue that CAVs are especially vulnerable to cyber-attacks due to their ability to store highly sensitive data and transmit such data on external communication networks. The GDPR also provides guidance on how organisations can comply with legal requirements (Mulder & Vellinga, 2021). These authors emphasize a three-step approach to cyber-security based on GDPR: first a data protection impact assessment (DPIA), secondly data protection by design, and finally data protection by default. Data protection by design and by default are legal obligations set in Article 25 of the GDPR. A DPIA can contribute to, amongst others, complying with these two obligations.

To address cybersecurity the EU enacted the first EU-wide legislation on cybersecurity, the NIS directive in August 2016 and has also released voluntary cybersecurity guidelines. In December 2016 the EU agency for Network and Information Security released best practices guidelines for the cybersecurity of connected vehicles. Cybersecurity and security concerning private data are important for building trust in and social acceptance of AVs (Lim & Taeihagh, 2018; Seetharaman et al., 2021). The GDPR also provides guidance on how organisations can comply with legal requirements (Mulder and Vellinga, 2021).

Vitunskaite et al. (2019) studied practices of cybersecurity in the cities of Barcelona, London and Singapore. They observe the following: "The real difficulty for observing security stems from the complexity of the smart city ecosystem and involvement of a high number of competing actors and stakeholders. As the cities are still developing, many fail to take these risks into account and develop an appropriate third-party management approach. One of the key symptoms of this deficiency is lack of appropriate standards and guidance, clearly defined roles and responsibilities and a common understanding of key security requirements. The case studies of Barcelona, Singapore and London has emphasised and corroborated the importance of technical standards, cyber security measures and an effective third-party management approach." (Vitunskaite et al., 2019)

In another paper on cybersecurity in the smart city, Habibzadeh et al. (2019) observe that it is common knowledge in the literature about public administration that information technology implementation projects are often derailed by non-technical challenges; issues of politics, bureaucracy, liability and other non-technical factors slow down the implementation of technology that is available. Also, with respect to security in the smart city it is often the case that new technologies have arrived and are deployed whereas personnel practices, security policies, and other agency and municipal practices tend to lag behind - resulting in a so called "security debt" (Habibzaheh et al., 2019; p. 4). These authors recommended that cities unambiguously define security roles of individuals in city administration, that they actively value security leadership, and that the cities form and maintains specialised security teams to carry out routine security measures such as training, firmware updates, developing emergency response plans, maintaining communications with different vendors and service provider

Khan et al. (2020) have studied the various cyber-attacks on automated vehicles and possible mitigation strategies from a perspective of the communication framework of CAVs. Based on the literature review, the leading automotive company reports, and the study of relevant government research bodies, Khan et al. (2020) have described the CAVs communication framework for all possible interfaces in the form of a flow-chart. The authors argue that this description has a three-fold value: first, it is imperative to have a systematic understanding of the CAVs communication framework; second, it is beneficial for monitoring, assessing, tracking, and combating potential cyber-attacks on various communication interfaces; third, it will facilitate the development of a robust CAVs cybersecurity- by-design paradigm by application developers. Important recommendations from their analysis are (Khan et al., 2020):

- CAVs and connected infrastructure require a continuous surveillance system to alert relevant operation centres immediately about any data or vehicle breaches
- system designers need to stay up to date with the advances in attacks on the CAV-embedded system
- manufacturers need to integrate security into every part of their designs
- in a coordinated approach to CAV cybersecurity ideally a shared problem-solving approach involves both road operators (as customers) and suppliers such as automotive manufacturers, equipment manufacturers, data aggregators and data processors

Readiness to engage social and ethical concerns

Introducing automated mobility will raise important social and ethical questions. In many publications on smart mobility in the smart city it has been emphasised that active education and engagement of citizens in policy development and decision-making is crucial for the successful implementation of CAVs and more broadly of CCAM (e.g., Alawadhi et al., 2020; Bezai et al., 2021; Briyik et al., 2021; Chng et al., 2021; Horizon 2020, 2020; McAslan et al. 2021; Milakis & Muller, 2021; Ayoma & Leon, 2021). User acceptance of automated vehicles will depend upon how the new automated mobility is perceived, how it will be used (shared or not, handling of privacy etc.) and what it will cost (Bezai et al., 2021). The city management has to provide and manage new technology that serves the needs of the city, i.e., the needs of its citizens: "New technologies are not ends in themselves but have to adapt to what serves the city. In the end, it is the municipalities that have to implement it" (Freadrich et al., 2018; p. 8).

The Horizon 2020 report on Ethics of connected and automated vehicles gives the following recommendations for preparing and engaging the public for CAVs (Horizon 2020, 2020; p. 68):

- inform and equip the public with the capacity to claim and exercise their rights and freedoms in relationship to AI in the context of CAVs
- ensure the development and deployment of methods for communication of information to all stakeholders, facilitating training, AI literacy, as well as wider public deliberation
- investigate the cognitive and technical challenges users face in CAV interactions and the tools to help them surmount these changes

Interestingly, Chng et al. (2021) have investigated citizen perceptions on driverless mobility by performing Citizen Dialogues, these are structured discussion meetings using both qualitative and quantitative methods, designed to be informative, deliberative and neutral to generate critical but unbiased insights. These dialogues were attended by more than 900 citizens in 15 cities across North America, Europe and Asia and the following was found:

- public transport was the preferred implementation model for driverless mobility, followed by ride-sharing and private car ownership
- the levels of trust and acceptance of automated vehicles tended to be lower at higher levels of vehicle automation
- citizens have reservations about whether industry will sufficiently safeguard citizens' interests; government should seek to support trust in industrial developments through regulation and oversight
- the citizens prefer their government to take active roles in driverless mobility and to set standards and regulations that safeguard and promote their interests

5 Conclusions and Recommendations

This chapter presents the main impacts of CAV and automated urban transport on environment, mobility, and society-safety-economy. Moreover, subsection 5.2 provides general recommendations and issues to be considered by city managers and policy makers.

5.1 Conclusions

Below we offer the main conclusions resulting from the work done in WP6.

- Increasing penetration levels of connected and automated vehicles in the urban city area are estimated (for most **baselines**) to have positive impacts on the environment (less emissions, higher energy efficiency), on society and economy (improved road safety, public health, and lower vehicle operating costs) and on mobility (more access to travel and less congestion). The predicted decrease in the modal share of public transport, walking and cycling in favour of automated passenger cars, however, may lead to some undesirable effects (such as the predicted increase in demand for parking space) without further policy measures.
- **Road use pricing** is expected to lead to a number of benefits above baseline developments, especially regarding mobility and environmental concerns: better energy efficiency, less reduction of active mode share, higher vehicle occupancy rate, less negative impact on public transport mode share, and less parking demand. On the negative side, road use pricing is expected to lead to an increase in vehicle operating costs, and lower accessibility to transport.
- **Dedicated CAV lanes** are predicted to have limited additional impacts on most indicators. Slight benefits were estimated for congestion, vehicle operating costs, vehicle utilisation and occupancy rates, as well as public health.
- **Parking price regulations** causing CAVs to return to other locations to park or drive around while waiting for passengers showed mixed results. Some negative effects are predicted on mobility (e.g. congestion), as well as the environment (energy efficiency), road safety, public health and accessibility of transport. These negative effects are primarily due to extra empty vehicle kilometres needed to reposition vehicles after passenger drop-off. However, increased parking costs also have the potential to stimulate a moderate mode shift away from private vehicle transport, which may benefit the use of active modes of travel and decrease the demand for parking space. Results regarding the effects on public transport use are mixed.
- Of the six major sub-use cases, **replacing on-street parking** is associated with a wide range of positive benefits over the baseline, including a large improvement in traffic conditions (reduced travel time and congestion), more positive development in active mode share, more shared mobility, better development of road safety and lesser demand for parking space. The facilities chosen to replace on-street parking also influence the impacts. Replacing on-street parking with public space is particularly associated with societal and environmental benefits (e.g. road safety, public health, energy efficiency) and is beneficial for shared, public, and active forms of mobility.

Replacing on-street parking with driving lanes or pick-up/drop-off points is generally associated with fewer benefits, except for improved access to travel. Pick-up/drop-off points or removing only half of spaces also reduce the benefits to congestion due to maintaining some of the parking manoeuvres.

- **Automated ride sharing** is expected to benefit vehicle sharing, accessibility, and energy efficiency. While it is predicted to attract a moderate mode shift away from private vehicle transport, automated ride sharing is also predicted to attract trips away from walking and cycling. Furthermore, the additional empty vehicle kilometres necessary to reposition the vehicles to pick up their next passengers may lead to an increase in congestion, counteracting the benefits of the trips which can be shared. The impact of an automated ride sharing system is also dependent on the population's willingness to share trips with other travellers: a higher willingness to share is associated with less negative effects on congestion and marginally better road safety.
- **GLOSA** is not predicted to have large additional impacts on most indicators. Slight benefits to the traffic conditions are predicted (reduced congestion and travel time) as well as less decrease in public transport use and reduced vehicle operating costs. Potential negative effects on shared mobility rate, active travel, vehicle utilisation and occupancy rates, access to travel and public health are predicted. These negative effects may be due to a predicted increase in private vehicle travel with implementation of GLOSA.
- The policies considered in the SUCs have little additional impact on generated emissions; the large, expected reductions are primarily driven by the transition to CAVs which are assumed to be electric vehicles. The large, expected improvements in road safety with increasing automation are also driven by behavioural differences in CAVs (e.g. quicker reaction times) compared to human-driven vehicles, which is impacted minimally by SUC policies.

5.2 Policy recommendations

The introduction of Cooperative, Connected and Automated Mobility (CCAM) and the implementation of interventions (sub-use cases) in the area of passenger cars is part of a wider transition towards smart and sustainable cities (Alawadhi et al., 2020; Aoyama & Leon, 2021; Bezai et al., 2020; Chng et al, 2021; Lim & Taeihagh, 2018; Vitunskaite et al., 2019; Mahdavian et al., 2021; McAslan et al., 2021; Medina et al., 2017; Milakis & Müller, 2021; Seuwou et al., 2019; Taeihagh & Lim, 2019). A successful transition will largely be impacted by the policy measures of the city, local and national authorities. Therefore, the LEVITATE project aims to support the authorities finding the most beneficial policies on the way towards an automated transport system.

General recommendations regarding CCAM

Based on recent literature dealing with the transition from a 100% human driver vehicle population to a 100% autonomous system without any human drivers (see Appendix D), the following recommendations can be suggested to make city managers and policy makers aware of what is to be done to support this transition and the overall success of CCAM)and use cases:

- City managers and policy makers should take into account four major areas of readiness for CCAM (autonomous driving): technology readiness, infrastructure readiness, legal readiness and the readiness to address social acceptance and ethical/social value issues (e.g., Alawadhi et al., 2020; Bezai et al., 2020)
- Commercial (technology) push alone will not safeguard the expected social benefits of CCAM (cooperative, connected and automated vehicles); new types of governance and

planning are called for with a stronger engagement of citizen groups and city stakeholders, a stronger focus on long term implications, and lesser reliance on traditional forecasting and traffic models (e.g., McAslan et al, 2021; Milakis & Müller, 2021)

- More anticipatory engaging styles of governance will not spontaneously develop; an anticipatory governance capacity has to be built (e.g., McAslan et al., 2021)
- Good legislation, guidance and guidelines for CCAM in Europe is already partly available (e.g., the GDPR, White Paper, Horizon Group report on Ethical guidelines). Authorities need to be aware of these and use these to survey what implications they have for planning and policy making at the city level (e.g., Mulder & Vellinga, 2021)
- There are many regulatory gaps for CCAM; using their own experiences and policy and planning orientations city managers, policy makers and planners should cooperate and contribute to the national and international debate about how these gaps should be resolved (e.g., Aoyama & Leon, 2021)
- The transition towards CCAM is as much a social and cultural phenomenon as a technological phenomenon; ultimately a lot if not all depends upon trust in new technology and trust will be easier to build if citizens have an active voice in what happens in their neighbourhoods (e.g., Chng et al., 2021; Medina et al., 2017; McAslan et al., 2021)
- The transition towards CCAM requires building of and participation in new broad alliances and platforms where many different actors from industry, and interest and citizen groups are present
- The risks concerning cybersecurity need a full understanding of the total digital communication framework and all interfaces of connected and automated vehicles; security-by-design is one of the most general and important principles to follow (e.g., Khan et al., 2020)
- The risks concerning cybersecurity cannot be solely managed by legislation and technocratic controlling strategies but demand social awareness, social education and cultural change in companies and citizens and third-party management (e.g., Khan et al., 2020; Vitunskaite et al., 2019)
- Back casting is one of the analytic methods that can help policy makers to make better informed decisions about how new technology can be implemented to achieve the expected benefits (e.g., Milakis & Müller, 2021).

Research in these various areas – new governance style, cybersecurity measures and culture, cooperation between varied stakeholder groups, regulatory gaps, citizen engagement, ethical concerns - can help develop a better understanding of problems and issues, possible solutions, and to better informed policy decisions.

Sub-use case related recommendations

- Automated vehicles may provide benefits such as additional comfort, efficiency, the potential for multitasking, and accessibility to travellers who are not able to drive a vehicle themselves. This may cause a potential modal shift from other modes of travel (e.g. public transport, cycling, walking) towards private vehicle travel, which may be undesirable to cities for a number of reasons (e.g. energy usage, public health, use of public space). In order to limit potential increases in private vehicle transport, road use pricing, replacing on-street parking with public space, and parking price regulation may be useful policy measures.
- Replacing on-street parking with public space is predicted to be associated with more benefits than replacing the space with driving lanes, provided care is taken that sufficient accessibility is retained.

- The benefits of an automated ride sharing system are highly dependent on the users' willingness to combine trips and it has the potential to increase congestion due to empty repositioning trips. Therefore, the suitability of local conditions for an automated ride sharing system should first be studied before implementation.
- GLOSA is associated with some moderate benefits to traffic conditions, although more efficient traffic flow may also attract more private vehicle use. Therefore, GLOSA may be best paired with other measures to encourage practices such as vehicle sharing and active travel.

References

Alawadhi, M., Almazrouie, J., Kamil, M., & Khalil, K.A. (2020). A systematic literature review of the factors influencing the adoption of autonomous driving. International Journal of System Assurance Engineering and Management, 11, 1065–1082. https://doi.org/10.1007/s13198-020-00961-4

Alkim, T., Bootsma, G., & Looman, P. (2007). De Rij-assistent: Systemen die het autorijden ondersteunen (Rijkswaterstaat, Ed.). Delft.

Anderson, J., Kalra, N., Stanley, K., Sorensen, P., Samaras, C., & Oluwatola, O. (2016). Autonomous Vehicle Technology: A Guide for Policymakers. https://doi.org/10.7249/RR443-2

Aoyama, Y., & Leon, L.F.A. (2021). Urban governance and autonomous vehicles. Cities, Volume 119, 103410. https://doi.org/10.1016/j.cities.2021.103410

AVV. (2001). Evaluatie Intelligente SnelheidsAanpassing (ISA): Het effect op het rijgedrag in Tilburg. Adviesdienst Verkeer en Vervoer.

Bertolini, A. & Riccaboni, M. (2021). Grounding the case for a European approach to the regulation of automated driving: the technology-selection effect of liability rules. European Journal of Law and Economics. http://doi.10.1007/s10657-020-09671-5

Bezai, N.E., Medjdoub, B., Al-Habaibeh, A., Chalal, M.L., & Fadli, F. (2021). Future cities and autonomous vehicles: analysis of the barriers to full adoption. Energy and Built Environment, 2(1), 65-81. https://doi.org/10.1016/j.enbenv.2020.05.002.

Biding, T., & Lind, G. (2002). Intelligent speed adaptation (ISA): results of large-scale trials in Borlange, Lidkoping, Lund and Umea during 1999-2002. In Publication / Vagverket, 2002:89 E. Retrieved from https://trid.trb.org/view/732737

Biswas, S., Chandra, S., & Ghosh, I. (2017). Effects of on-street parking in urban context: A critical review. Transportation in developing economies, 3(1), 10. DOI 10.1007/s40890-017-0040-2

Bıyık, C., Abareshi, A., Paz, A., Ruiz, R.A., Battarra, R., Rogers, C.D.F., & Lizarraga, C. (2021). Smart Mobility Adoption: A Review of the Literature. Journal of Open Innovation: Technology, Market and Complexity, 7, 146. https://doi.org/10.3390/joitmc7020146

Boghani, H.C., Papazikou, E., Zwart, R.d., Roussou, J., Hu, B., Filtness, A., & Papadoulis, A., (2019). Defining the future of passenger car transport, Deliverable D6.1 of the H2020 project LEVITATE.

Borovskoy, A., & Yakovleva, E. (2017). Simulation Model of Parking Spaces Through the Example of the Belgorod Agglomeration. Transportation Research Procedia, 20, 80-86. DOI: 10.1016/j.trpro.2017.01.019.

Bose, A., & Ioannou, P.A. (2003). Analysis of traffic flow with mixed manual and semiautomated vehicles. IEEE Transactions on Intelligent Transportation Systems, 4(4), 173–188. https://doi.org/10.1109/TITS.2003.821340

Burkacky, O., Deichmann, J., Klein, B., Pototzky, K., & Scherf, G. (2020). Cybersecurity in automotive: Mastering the challenge. Munich, McKinsey.

Carsten, O.M.J., & Tate, F. (2000). External Vehicle Speed Control Final Report: Integration. Institute for Transport Studies, University of Leeds.

Carsten, O., & Martens, M.H. (2019). How can humans understand their automated cars? HMI principles, problems and solutions. Cognition, Technology & Work, 21, 3–20. https://doi.org/10.1007/s10111-018-0484-0

Cavoli, C., Phillips, B., Cohen, T., & Jones, P. (2017). Social and behavioural questions associated with Automated Vehicles A Literature Review. UCL Transport Institute January.

Chai, H. et al. (2020). The Impacts of Automated Vehicles on Center City Parking Demand. Available at: https://doi.org/10.7922/G2X928J1.

Chapin, T., Stevens, L., Crute, J., Crandall, J., Rokyta, A., & Washington, A. (2016). Envisioning Florida's Future: Transportation and Land Use in an Automated Vehicle Automated Vehicle World. Florida Department of Transportation, Tallahassee.

Chaudhry, A., Sha, H., Haouari R., Zach, M., Boghani, H.C., Singh, M., Gebhard, S., Zwart, R.d., Mons, C., Weijermars, W., Hula, A., Roussou, J., Richter, G., Hu, B., Thomas, P., Quddus, M., & Morris, A. (2021). The long-term impacts of cooperative and automated cars, Deliverable D6.4 of the H2020 project LEVITATE

Chira-Chavala, T., & Yoo, S. M. (1994). Potential safety benefits of intelligent cruise control systems. Accident Analysis and Prevention, 26(2), 135–146. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/8198682

Chng, S., Kong, P., Lim, P.Y., Cornet, H., & Cheah, L. (2021). Engaging citizens in driverless mobility: Insights from a global dialogue for research, design and policy, Transportation Research Interdisciplinary Perspectives, 11, 100443, https://doi.org/10.1016/j.trip.2021.100443

Cicchino, J.B. (2017). Effectiveness of forward collision warning and autonomous emergency braking systems in reducing front-to-rear crash rates. Accident Analysis and Prevention, 99(Pt A), 142–152. https://doi.org/10.1016/j.aap.2016.11.009

City of Manchester (2017). The Greater Manchester Transport Strategy 2040. First published February 2017.

City of Vienna (2015). Urban Mobility Plan Vienna. Available at https://www.wien.gv.at/stadtentwicklung/studien/pdf/b008443.pdf.

Comte, S.L., & Jamson, A.H. (2000). Traditional and innovative speed-reducing measures for curves: an investigation of driver behaviour using a driving simulator. Safety Science, 36(3), 137–150. https://doi.org/10.1016/s0925-7535(00)00037-0

Davis, B., Morris, N., Achtemeier, J., & Patzer, B. (2018). In-Vehicle Dynamic Curve-Speed Warnings at High-Risk Rural Curves. Minnesota Department of Transportation.

DiMaggio, C., & Durkin, M. (2002). Child pedestrian injury in an urban setting descriptive epidemiology. Academic emergency medicine, 9(1), 54-62.

Edquist, J., Rudin-Brown, C.M., & Lenné, M.G. (2012). The effects of on-street parking and road environment visual complexity on travel speed and reaction time. Accident Analysis & Prevention, 45, 759-765.

EEA (2020). Air quality in Europe — 2020 report. European Environment Agency. https://www.europarl.europa.eu/meetdocs/2014_2019/plmrep/COMMITTEES/ENVI/DV/2021/01-14/Air_quality_in_Europe-2020_report_EN.pdf

Elvik, R. et al. (2019). A taxonomy of potential impacts of connected and automated vehicles at different levels of implementation. Deliverable D3.1 of the H2020 project LEVITATE.

Elvik, R., Meyer, S.F., Hu, B., Ralbovsky, M., Vorwagner, A., & Boghani, H. (2020). Methods for forecasting the impacts of connected and automated vehicles, Deliverable D3.2 of the H2020 project LEVITATE.

ERTRAC (2019). Connected Automated Driving Roadmap. Retrieved fromhttps://www.ertrac.org/index.php?page=ertrac-roadmap

European Commission (2017). Towards clean, competitive and connected mobility: the contribution of Transport Research and Innovation to the Mobility package, SWD (2017) 223 final.

Eurorap (2013). Roads that cars can read: A Quality Standard for Road Markings and Traffic Signs on Major Rural Roads - Proposals for consultation. Basingstoke, UK, Eurorap.

Evas, T. (2018). A Common EU Approach to Liability Rules and Insurance for Connected and Autonomous Vehicles: European Added Value Assessment: Accompanying the European Parliament's legislative own-initiative report. Brussels, European Parliamentary Research Service. Retrieved from: https://www.europarl.europa.eu/RegData/etudes/STUD/2018/615635/EPRS_STU(2018)615635_EN.pdf

Fadairo G. (2013). Traffic congestion in Akure, Ondo State, Nigeria: using Federal University of Technology Akure Road as a case study. International Journal of Science Arts and Commerce 2, 67–76.

Fagnant, D.J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, 77, 167–181. https://doi.org/10.1016/J.TRA.2015.04.003

Farmer, C. (2008). Crash Avoidance Potential of Five Vehicle Technologies (p. 23). p. 23. Insurance Institute for Highway Safety.

Fildes, B., Keall, M., Bos, N., Lie, A., Page, Y., Pastor, C., & Tingvall, C. (2015). Effectiveness of low-speed autonomous emergency braking in real-world rear-end crashes. Accident Analysis and Prevention, 81, 24–29. https://doi.org/10.1016/j.aap.2015.03.029

Fraedrich, E., Heinrichs, D., Bahamonde-Birke, F. J., & Cyganski, R. (2019). Autonomous driving, the built environment and policy implications. Transportation Research Part A: Policy and Practice, 122(March 2018), 162–172. https://doi.org/10.1016/j.tra.2018.02.018

González-González, E., Nogués, S. & Stead, D. (2020). Parking futures: Preparing European cities for the advent of automated vehicles. Land Use Policy, 91(August 2018), p. 104010. doi: 10.1016/j.landusepol.2019.05.029.

González-González, E., Nogués, S., & Stead, D. (2019). Automated vehicles and the city of tomorrow: A backcasting approach. Cities, 94, 153–160. https://doi.org/10.1016/J.CITIES.2019.05.034

Gruyer, D., Orfila, O., Glaser, S., Hedhli, A., Hautiere, N., & Rakotonirainy, A. (2021) Are Connected and Automated Vehicles the Silver Bullet for Future Transportation Challenges? Benefits and Weaknesses on Safety, Consumption, and Traffic Congestion. In Frontiers in Sustainable Cities, 2, p. 63.

Guo, H., Gao, Z., Yang, X., Zhao, X., & Wang, W. (2012). Modeling travel time under the influence of on-street parking. Journal of Transportation Engineering, 138(2), 229-235. doi: 10.1061/(ASCE)TE.1943-5436.0000319.

Habibzadeh, H., Nussbaum, B.H., Anjomshoa, F., Kantarci, B., & Soyata, T. (2019). A survey on cybersecurity, data privacy, and policy issues in cyber-physical system deployments in smart cities, Sustainable Cities and Society, 50. https://doi.org/10.1016/j.scs.2019.101660.

Haider, M.A., Islam, M.T., & Hasan, S.M. (2021). Exploring the impact of on-street parking in Chittagong City, Bangladesh. International Journal of Building, Urban, Interior and Landscape Technology (BUILT), 17, 17-28. Retrieved from https://ph02.tci-thaijo.org/index.php/BUILT/article/view/242401

Haouari, R., Chaudhry, A., Sha, H., Richter, G., Singh, M., Boghani, H.C., Roussou, J., Hu, B., Thomas, P., Quddus, M., & Morris, A. (2021). The short-term impacts of cooperative, connected, and automated mobility on passenger transport, Deliverable D6.2 of the H2020 project LEVITATE.

Hibberd, D., Louw, T., et al. (2018). From research questions to logging requirements. Deliverable D3.1. L3 Pilot Driving Automation. University of Leeds.

Highway Loss Data Institute. (2019). Real-world benefits of crash avoidance technologies. Arlington, VA: Insurance Institute for Highway Safety.

Horizon 2020 (2020). Ethics of Connected and Automated Vehicles: recommendations on road safety, privacy, fairness, explainability and responsibility. Luxembourg, Publication Office of the European Union.

Hummel, T., Kühn, M., Bende, J., Lang, A., & Research, I.A. (2011). Advanced Driver Assistance Systems: An Investigation of their Potential Safety Benefits Based on an Analysis of Insurance Claims in Germany (p. 64) Berlin: German Insurance Association.

Hynd, D., McCarthy, M., Carroll, J., Seidl, M., Edwards, M., Visvikis, C., … & Stevens, A. (2015). Benefits and Feasibility of a Range of New Technologies and Unregulated Measures in the fields of Vehicle Occupant Safety and Protection of Vulnerable Road Users (p. 470). p. 470. https://doi.org/10.2769/497485

ITF/OECD (2015). Urban Mobility System Upgrade How shared self-driving cars could change city traffic. Accessed 21 October at: https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf

Jenness, J., Lerner, N., Mazor, S., Osberg, J., & Tefft, B. (2007). Use of Advanced in-Vehicle Technology by Young and Older Early Adopters. Survey Results on Sensor-Based Backing Aid Systems and Rear-View Video Cameras. National Highway Traffic Safety Administration.

Jermakian, J.S. (2011). Crash avoidance potential of four passenger vehicle technologies. Accident Analysis and Prevention, 43(3), 732–740. https://doi.org/10.1016/j.aap.2010.10.020

Kessler, C., Etemad, A., Alessandretti, G., Heinig, K., Selpi, Brouwer, R., … & Benmimoun, M. (2012). Deliverable D11.3: Final Report. EuroFOT - European Field Operational Test on Active Safety Systems.

Khan, S.K., Shiwakoti, N., Stasinopoulos, P. & Chen, Y. (2020). Cyber-attacks in the next-generation cars, mitigation techniques, anticipated readiness and future directions. Accident Analysis & Prevention, 148. https://doi.org/10.1016/j.aap.2020.105837

Korse, M.J., Schermers, G., Radewalt, N.M.D., de Hoog, A., Alkim, T. 2004. On track. Results of the trial of LDWA systems. Rotterdam, Th e Netherlands: Transport Research Centre (AVV) of the Dutch Ministry of Transport, Public Works and Water Management. (https://puc.overheid.nl/rijkswaterstaat/doc/PUC_116055_31/)

Kusano, K. D., & Gabler, H. C. (2012). Safety Benefits of Forward Collision Warning, Brake Assist, and Autonomous Braking Systems in Rear-End Collisions. IEEE Transactions on Intelligent Transportation Systems, 13(4), 1546–1555. https://doi.org/10.1109/tits.2012.2191542

Kusano, K.D., & Gabler, H.C. (2015). Comparison of Expected Crash and Injury Reduction from Production Forward Collision and Lane Departure Warning Systems. Traffic Injury Prevention, 16, S109–S114. https://doi.org/10.1080/15389588.2015.1063619

Kyriakidis, M., Winter, J.C.F de, Stanton, N., Bellet, T., Arem, B van, et al. (2017). A Human Factors Perspective on Automated Driving. Theoretical Issues in Ergonomics Science, Taylor & Francis, 1-27. https://doi.10.1080/1463922X.2017.1293187

Lee, D., & Hess, D.J. (2020). Regulations for on-road testing of connected and automated vehicles: Assessing the potential for global safety harmonization. *Transportation Research Part A: Policy and Practice, 136*, 85-98. https://doi.org/10.1016/j.tra.2020.03.026

Lim, H.S.M. & Taeihagh, A. (2018). Autonomous Vehicles for Smart and Sustainable Cities: An In-Depth Exploration of Privacy and Cybersecurity Implications. Energies, 11, 1062.

Liu, N., Nikitas, A., & Parkinson, S. (2020). Exploring expert perceptions about the cyber security and privacy of Connected and Autonomous Vehicles: A thematic analysis approach. Transportation Research Part F,75, 66-86.

Liu, Y., Tight, M., Sun, Q., & Kang, R. (2019). A systematic review: Road infrastructure requirement for Connected and Autonomous Vehicles (CAVs). Journal of Physics: Conference Series, 1187, 042073.

Lyon, B., Hudson, N., Twycross, M., Finn, D., Porter, S., Maklary, Z., & Waller, T. (2017). Automated vehicles do we know which road to take. Infrastructure Partnerships Australia.

Lytrivis, A., Manganiaris, S., Reckenzaun, J., Solmaz, S., Protzmann, R., Adaktylos, A.-M., Wimmer, Y., Atasayar, H., Daura, X., & Porcuna, D. (2019). Deliverable. D.5.4 Infrastructure Classification Scheme. INFRAMIX – Road INFRAstructure ready for MIXed vehicle traffic flows

Ma, K., & Wang, H. (2019). Influence of Exclusive Lanes for Connected and Autonomous Vehicles on Freeway Traffic Flow. IEEE Access, 7, 50168–50178.

Mahdavian, A., Shojaei, A., Mccormick, S., Papandreou, T., Eluru, N., & Oloufa, A.A. (2021). Drivers and Barriers to Implementation of Connected, Automated, Shared, and Electric Vehicles: An Agenda for Future Research. IEEE Access 9, 22195-22213.

Mardirossian, V. (2020). Will Autonomous Cars Put an End to the Traditional Third-Party Liability Insurance Coverage? In P. Marano & K. Noussia (Eds.), *In InsurTech: A Legal and Regulatory View* (pp. 271-290). Switzerland: Springer-Verlag.

Martin, A. (2006). Factors influencing pedestrian safety: a literature review (No. PPR241). Wokingham, Berks: TRL.

Masera, C., Imprialou, M., Budd, L., &Morton, C. (2019). Estimating the traffic impacts of green light optimal speed advisory systems using microsimulation. International journal of Transport Vehicle Engineering, 13(1), 22-29.

McAslan, D., Gabriele, M. & Miller, T.R. (2021) Planning and Policy Directions for Autonomous Vehicles in Metropolitan Planning Organizations (MPOs) in the United States, Journal of Urban Technology. https://doi.org/10.1080/10630732.2021.1944751

Medina, A., Maulana, A., Thompson, D., Shandilya N., Almeida, S., Aapaoka A., & Kutila, M. (2017). Public Support Measures for Connected and Automated Driving: Final Report. GROW-SME-15-C-N102. European Commission EC. EU Publications, No. EA-01-17-634-EN-N. https://ec.europa.e

Mellegård, N., & Reichenberg, F. (2020). The Day 1 C-ITS Application Green Light Optimal Speed Advisory—A Mapping Study. Transportation Research Procedia. 49. 170-182. 10.1016/j.trpro.2020.09.015.

Milakis, D., & Müller, S. (2021). The societal dimension of the automated vehicles transition: Towards a research agenda. Cities, 113, 103144, https://doi.org/10.1016/j.cities.2021.103144.

Milakis, D., Van Arem, B. & Van Wee, B. (2017). Policy and society related implications of automated driving: A review of literature and directions for future research. Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, 21(4), pp. 324–348. doi: 10.1080/15472450.2017.1291351.

Mohajerpoor, R., & Ramezani, M. (2019). Mixed flow of autonomous and human-driven vehicles: Analytical headway modeling and optimal lane management. Transportation Research Part C: Emerging Technologies, 109(October), 194–210. https://doi.org/10.1016/j.trc.2019.10.009

Moore, M., & Zuby, D. (2013). Collision Avoidance Features: Initial Results (p. 8). p. 8. Highway Loss Data Institute, Insurance Institute for Highway Safety.

Morales-Alvarez, W., Sipele, O., Léberon, R., Tadjine, H.H., & Olaverri-Monreal, C. (2020) Automated Driving: A Literature Review of the Takeover Request in Conditional Automation. Electronics. 9(12):2087. https://doi.org/10.3390/electronics9122087

Morsink, P., Goldenbeld, C., Dragutinovic, N., Marchau, V., Walta, L., & Brookhuis, K. (2007). Speed support through the intelligent vehicle. Leidschendam: SWOV Institute for Road Safety Research.

Mulder, T., Vellinga, N.E. (2021) Exploring data protection challenges of automated driving. In Computer Law & Security Review, 40(105530)

Nahry et al. (2019). Modeling the relationship between on-street parking characteristics and through traffic delay. Proceedings of the Pakistan Academy of Sciences: Part A, 56(2), pp. 29–36.

OECD/ITF. (2015). Automated and Autonomous Driving: Regulation under Uncertainty.

Othman, K. (2021). Impact of autonomous vehicles on the physical infrastructure: Changes and challenges. Designs, 5(3). doi: 10.3390/designs5030040.

Papazikou, E., Zach, M., Boghani, H.C., Elvik, R., Tympakianaki, A., Nogues, L., & Hu, B. (2020). Detailed list of sub-use cases, applicable forecasting methodologies and necessary output variables, Deliverable D4.4 of the H2020 project LEVITATE. Pierowicz, J., Jocoy, E., Lloyd, M., Bittner, A., & Pirson, B. (2000). Intersection Collision Avoidance Using ITS Countermeasures: Final Report. National Highway Traffic Safety Administration.

Praburam, G., & Koorey, G. (2015). Effect of on-street parking on traffic speeds. IPENZ Transportation Group Conference, (April), p. 6905.

Prakash P., Bandyopadhyaya R., Sinha S. (2020). Study of Effect of On-Street Parking on Traffic Capacity. Transportation Research. Lecture Notes in Civil Engineering, vol 45. Springer, Singapore. https://doi.org/10.1007/978-981-32-9042-6_32.

Qian, Z. (Sean), & Rajagopal, R. (2014). Optimal dynamic parking pricing for morning commute considering expected cruising time. Transportation Research Part C: Emerging Technologies, 48, 468–490. https://doi.org/10.1016/j.trc.2014.08.020

Radivojevic, D., Stevanovic, J., & Stevanovic, A. (2016). Impact of Green Light Optimized Speed Advisory on Unsignalized Side-Street Traffic. Transportation Research Record: Journal of the Transportation Research Board. 2557. 24-32. 10.3141/2557-03.

Rakha, H., Hankey, J., Patterson, A., & Van Aerde, M. (2001). Field evaluation of safety impacts of adaptive cruise control. Journal of Intelligent Transport Systems, 6(3), 225–259. https://doi.org/10.1080/10248070108903694

Regan, M., Triggs, T., Young, K., Tomasevic, N., Mitsopoulos, E., Stephan, K., & Tingvall, C. (2006). On-road evaluation of intelligent speed adaptation, following distance warning and seatbelt reminder systems: final results of the TAC SafeCar Project. Clayton: Monash University Accident Research Centre.

Rendant, K., & Geelen, van (2020). Connected & Autonomous Vehicles and road infrastructure State of play and outlook. Brussels, Belgian Road Research Centre.

Saeed, T.U., Alabi, B.N.T., & Labi, S. (2020). Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective. Journal of Infrastructure Systems, https://doi.1061/(ASCE)IS.1943-555X.0000593

Scanlon, J.M., Sherony, R., & Gabler, H.C. (2017). Injury mitigation estimates for an intersection driver assistance system in straight crossing path crashes in the United States. Traffic Injury Prevention, 18, S9–S17. https://doi.org/10.1080/15389588.2017.1300257

Schwebel, D.C., Davis, A.L., & O'Neal, E.E. (2012). Child pedestrian injury: A review of behavioral risks and preventive strategies. American journal of lifestyle medicine, 6(4), 292-302.

Seetharaman, A., Patwa, N., Jadhav, V., Saravanan A.S., & Sangeeth D. (2021) Impact of Factors Influencing Cyber Threats on Autonomous Vehicles. Applied Artificial Intelligence, 35:2, 105-132, DOI: 10.1080/08839514.2020.1799149

Seuwou, P., Banissi, E., & Ubakanma, G. (2019). The Future of Mobility with Connected and Autonomous Vehicles in Smart Cities. In The Future of Mobility with Connected and Autonomous Vehicles in Smart Cities (pp. 37-52). Springer Nature.

Sha, H., Boghani, H., Chaudhry, A., Quddus, M., Morris, A., Thomas, P. (2021). LEVITATE: Passenger Cars Microsimulation Sub-use Cases Findings. LEVITATE (Horizon 2020), January 2021

Sha, H., Chaudhry, A., Haouari R., Zach, M., Richter, G., Singh, M., Boghani, H.C., Roussou, J., Hu, B., Thomas, P., Quddus, M., & Morris, A. (2021). The medium-term impacts of CCAM on passenger transport, Deliverable D6.3 of the H2020 project LEVITATE

Sternlund, S., Strandroth, J., Rizzi, M., Lie, A., & Tingvall, C. (2017). The effectiveness of lane departure warning systems: A reduction in real-world passenger car injury crashes. Traffic Injury Prevention, 18(2), 225–229. https://doi.org/10.1080/15389588.2016.1230672

Sugiarto, S., & Limanoond, T. (2013). Impact of On-street Parking on Urban Arterial Performance: A Quantitative Study on Travel Speed and Capacity Deterioration. International Journal of Science and Technology, 2(2), 63–69. doi: 10.13170/aijst.0202.04.

SWOV (2021). Snelheid en snelheidsmanagement. SWOV factsheet, the Hague, the Netherlands (www.swov.nl)

Taeihagh, A., & Lim, H.S.M. (2019). Governing autonomous vehicles: emerging responses for safety, liability, privacy, cybersecurity, and industry risks. *Transport Reviews, 39* (1), 103-128.

Eliasson, J., Hultkrantz, L., Nerhagen, L., & Smidfelt-Rosqvist, L. (2009). The Stockholm congestion – charging trial 2006: Overview of effects. Transportation Research Part A: Policy and Practice, 43(3), https://doi.org/10.1016/j.tra.2008.09.007.

Transport for London (2007). Central London Congestion Charging Scheme: Ex-post Evaluation of the Quantified Impacts of the Original Scheme, www.tfl.gov.uk/assets/downloads/Ex-post-evaluation-of-quantified-impacts-of-original-scheme-07-June.pdf, accessed 13 October 2008

Vaa, T., Assum, T., & Elvik, R. (2014). Driver support systems: Estimating road safety effects at varying levels of implementation. Oslo: Institute of Transport Economics.

Van der Zweep, C., Pla, M., Wisch, M., Schaller, T., De Hair, S., & Lemmen, P. (2014). ASPECSS: Assessment methodologies for forward looking Integrated Pedestrian and further extension to Cyclists Safety. European Commission.

Vander Laan, Z., & Sadabadi, K.F. (2017). Operational performance of a congested corridor with lanes dedicated to autonomous vehicle traffic. International Journal of Transportation Science and Technology, 6(1), 42–52. https://doi.org/10.1016/j.ijtst.2017.05.006

Vellinga, N.E. (2019) Automated driving and its challenges to international traffic law: which way to go*? Law, Innovation and Technology, 11*(2), 257-278. https://doi.org/10.1080/17579961.2019.1665798

Vitunskaite, M., He, Y., Brandstetter, T., & Janicke, H. (2019). Smart cities and cyber security: Are we there yet? A comparative study on the role of standards, third party risk management and security ownership. Computers & Security, 83, 313-331.

Weijermars et al. (2021) Levitate: road safety impacts of Connected and Automated vehicles. Web-article updated version July 2021. H2020 LEVITATE project.

Wu, K.F., Ardiansyah, M.N., & Ye, W.J. (2018). An evaluation scheme for assessing the effectiveness of intersection movement assist (IMA) on improving traffic safety. Traffic Injury Prevention, 19(2), 179–183. https://doi.org/10.1080/15389588.2017.1363891

Xia, B., et al. (2021). Sustainable renewal methods of urban public parking spaces under the scenario of shared autonomous vehicles (Sav): A review and a proposal. Sustainability (Switzerland), 13(7). doi: 10.3390/su13073629.

Yanagisawa, M., Swanson, E., & Najim, W.G. (2014). Target Crashes and Safety Benefits Estimation Methodology For Pedestrian Crash Avoidance/Mitigation Systems (D. of Transportation, Ed.). Washington, DC: National Highway Traffic Safety Administration.

Ye, L., & Yamamoto, T. (2018). Impact of dedicated lanes for connected and autonomous vehicle on traffic flow throughput. Physica A: Statistical Mechanics and Its Applications, 512, 588–597. https://doi.org/10.1016/j.physa.2018.08.083

Appendix A Methods and operationalisations

In this Appendix we describe the main methods used to estimate the impacts within WP6, namely traffic microsimulation, Delphi, mesosimulation and system dynamics.

In essence, *microscopic traffic simulation models* simulate the movement of individual vehicles on a pre-defined road network using a combination of vehicle and driver models that approximate car-following and lane-changing theories and thereby allowing the forecasting of traffic-related impacts. Traffic simulations are the most commonly applied method for predicting the impacts of connected and automated vehicles (Elvik et al., 2020). Traffic simulations have been used to study several potential impacts of connected and automated vehicles, including impacts on road capacity, intersection capacity and performance (stops and delays), traffic volume, travel time, fuel consumption, road accidents etc. The results of most microsimulation studies show potential impacts of connected and automated vehicles as a function of their market penetration rate (Elvik et al., 2020).

In WP6, microscopic simulation was used to study the impacts of 5 policy interventions (sub-use cases) on CO_2-emission, congestion, total kilometres travelled and traffic safety. The policy interventions were:
1. Provision of dedicated lanes for AVs on urban highways
2. Parking price regulation
3. Parking space regulation
4. Automated ride sharing
5. Green Light Optimal Speed Advisory (GLOSA)

In WP6 of LEVITATE the *Delphi method* was also used to estimate the effects of 6 SUC's and to identify the experts' vision of the future related to CCAM. The Delphi method is a systematic and qualitative method of forecasting which is based on collecting opinions from a group of experts by means of a series of related questions. The questions were related to the specific policy interventions, or sub-use cases (SUCs), and experts were asked to give their opinion on the effect of these SUCs on the different impact areas. The Delphi uses a process of repeated testing whereby results of a first round of questions are communicated back to the group and the questions repeated at a later stage in a second round to see if respondents change opinions.

In order to keep questionnaire length manageable, the participants were divided into several groups. 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.

Mesoscopic simulation is a supplemental method within the group of simulation approaches which emphasise the modelling of behaviours and choices of individuals (Elvik et al., 2020). Such an activity-based-modelling (ABM) framework is realised by the mesoscopic traffic simulation tools of MATSim. "Mesoscopic" in this context underlines the fact that the method is less focussed on immediate interactions between road users, thus reducing the level and complexity of these details, but rather on the choices people (represented as agents is a mesoscopic model) make to re-arrange their daily routes and schedules of activities. Each of the activities within a complete daily chain or "plan" are preferably reached in time by the means of transport available to each person (agent) within the simulated area under investigation. The major conclusions that can be extracted from such models refer to changes in modal split, as well as differences in road network loads and vehicle utilization (Elvik et al., 2020). Mesoscopic simulation and activity-based-modelling are well-suited for assessing modal split, road network loads and vehicle utilisation rate (Elvik et al., 2020).

The types of impacts studied within LEVITATE have been estimated and forecasted using various assessment methods, such as traffic microsimulation, system dynamics and the Delphi panel method. In the study design it was anticipated to use traffic microsimulation to estimate direct impacts and mesosimulation for the systemic impacts whereas the Delphi would supplement these and together with systems dynamics would also provide estimates for the wider impacts. Traffic microsimulation can be used to forecast direct impacts (which have an immediate to long term effect) and are suitable to develop relationships that can infer dose (in terms of introduction of sub-use case) and response (selected impact). Traffic microsimulation also provides further input to assess medium-term impacts by processing those results appropriately to infer such impacts.

The mesoscopic simulation is used as a method to estimate the impacts of road-use pricing on average travel times an amount of travel per person.

System level analysis (such as by tools found within system dynamics) can provide measure of long-term impacts. *System dynamics* is a modelling technique where the whole system is modelled at an abstract level by modelling the sub-systems at component level and aggregating the combined output (Bogdani & Zach, 2020). This allows researchers to use feedback/feedforward from one component to another within the system, which unfolds when output is viewed against time. System dynamics is a powerful way of modelling a system at an abstract level. Final points on its strengths and usefulness can be summarised as below (Bogdani & Zach, 2020):

- Feedback within the system can be handled easily and one can see the effect of complex feedback via numerical simulations.

- Interconnected systems can be integrated very well and allows one to extend the model as well.
- Structure determines behaviour – same model, different behaviours due to states of sub-systems/constituents.
- Future values depend on past values.
- Mathematical complexity of large complex system does not hinder modelling, as the system is solved by using solvers using discretised system.
- Allows one to play with 'what if' scenarios easily and faster. It allows one to change the strength and timing of external disturbances as well as of policy measures that might be applied.
- Provides a deeper understanding of the system, as one knows what effects are generated in the system, due to a particular cause presented to it

For the sake of simplicity and applicability of these 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 implementing 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).

Appendix B Behavioural Assumptions microsimulation AIMSUN

Two types of connected and automated vehicles (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. The automation of freight vehicles was also considered in this study, however due to limited knowledge on freight CAVs, only a few parameters were adjusted to model the behaviours of freight CAVs. 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.

The assumptions on CAV parameters and their values were based on comprehensive literature review, including both empirical and simulation-based studies, as well as discussions in meetings with experts, conducted as part of LEVITATE project. Some guidance on the behaviours was also obtained through studies on ACC and CACC systems. The key parameters which were changed to model the driving behaviours of CAVs along with the associated assumptions are as presented in *Table B.1* below:

Table B.1 Human-driven vehicle and CAV Parameters

Parameter	Description	Human-Driven Vehicle	1st Generation CAV	2nd Generation CAV
Time gap In Aimsun, reaction time along with sensitivity factor, affects time gap	Time that elapses between rear end of the lead vehicle and front bumper of following vehicle.	Lesser than 1st Gen CAV	More than HDVs	Shorter than HDVs and 1st Gen CAVs
Max. acceleration	maximum acceleration that a vehicle can achieve under any circumstances	Larger average acceleration and range	Lesser average acceleration and range than HDVs (comfortable ride experience)	Lesser than HDVs and 1st Gen CAVs (comfortable ride experience)

Normal deceleration	maximum deceleration a vehicle can use under normal conditions	Larger variation in deceleration	Lesser variation in deceleration than HDVs (comfortable ride experience)	Lesser variation in range than HDVs (comfortable ride experience)
Max. deceleration	Maximum deceleration a vehicle can use under special circumstances, such as emergency braking.	Less than CAVs	More than HDVs	More than HDVs and 1st Gen CAVs
Clearance	The distance a vehicle keeps between itself and the leading vehicle when stopped.	More variability in clearance	Lesser variation in clearance than HDVs	Lesser variation in clearance than HDVs
Safety margin factor	It generates give-way behaviour at 95 unsignalized junctions. The higher the value indicated more cautious behaviour.	Lesser than 1st Gen CAV	Higher than HDVs, (cautious behaviour)	Shorter than HDVs (assertive behaviour)
Look ahead distance factor (anticipation of lane change)	It determines where the vehicles consider their lane change	More variation	1st generation CAVs will consider changing lane earlier than human-driven vehicles would, due to limited situational awareness	2nd generation CAVs will consider changing lane later than human-driven vehicles would, due to advanced situational awareness
Overtaking	It controls overtaking manoeuvres when a vehicle changes lane to pass another.	Defaults in Aimsun	conservative driving behaviour. Same logic as of HDVs	Aggressive lane change logic compared to human-driven vehicles,
Time gap	Time that elapses between rear end of the lead vehicle and front bumper of following vehicle	Lesser than 1st Gen CAVs	More than HDVs	Shorter than HDVs and 1st Gen CAVs
Max. acceleration	Maximum acceleration that a vehicle can achieve under any circumstances	Larger average acceleration and range	Lesser average acceleration and range than HDVs (comfortable ride experience)	Lesser than HDVs and 1st Gen CAVs (comfortable ride experience)
Max. deceleration	Maximum deceleration a vehicle can use under special circumstances, such as emergency braking	Less than CAVs	More than HDVs	More than HDVs and 1st Gen CAVs
Clearance	The distance a vehicle keeps between itself and the leading vehicle when stopped.	More variability in clearance	Lesser variation in clearance than HDVs	Lesser variation in clearance than HDVs
Safety margin factor	It generates give-way behaviour at 95 unsignalized junctions. The higher the value indicated more cautious behaviour	Lesser than 1st Gen CAV	Higher than HDVs, (cautious behaviour)	Shorter than HDVs (assertive behaviour)

Look ahead distance factor (anticipation of lane change)	It determines where the vehicles consider their lane change	More variation	1st generation CAVs will consider changing lane earlier than HDVs would	2nd generation CAVs will consider changing lane later than HDVs would
Overtaking	It controls overtaking manoeuvres when a vehicle changes lane to pass another	Defaults in Aimsun	Conservative driving behaviour. Same logic as of HDVs	Aggressive lane change logic compared to HDVs

Appendix C Microsimulation networks

C.1 Networks per sub-use case

The following network descriptions are taken from LEVITATE Deliverable 6.3 (Sha et al., 2021). For the full explanations of microsimulation methodology, see Deliverables 6.2-6.4.

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 C.1*) which connect the centre of Manchester with the suburbs.

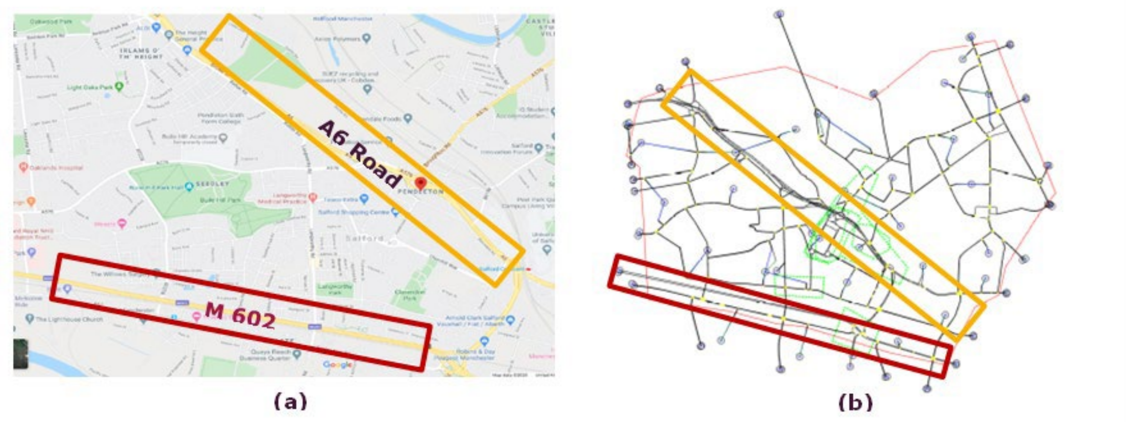


Figure C.1: The modelling area in the city of Manchester (a) and Manchester network in AIMSUN software (b)

<u>Assumptions and parameters</u>

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.

Parking price regulation
A microsimulation model of Santander City was employed for this sub-use case (*Figure C.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.

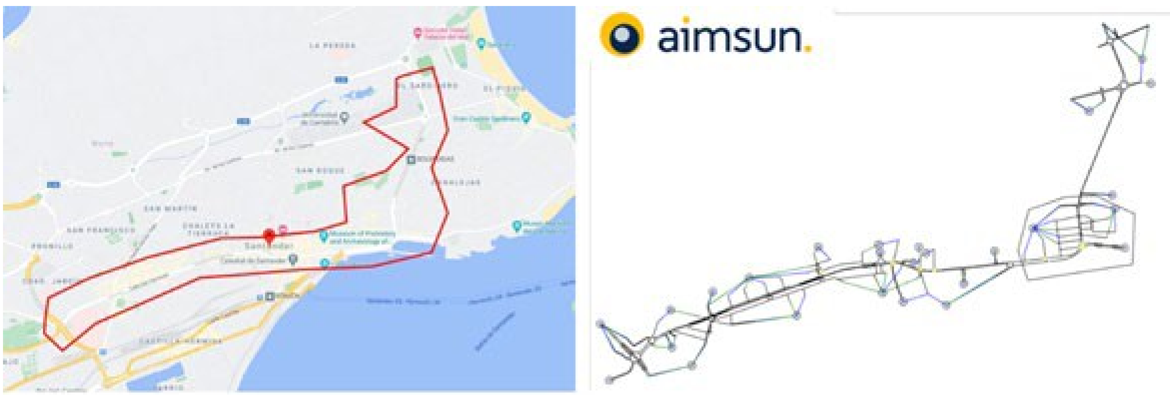


Figure C.2: The modelling area in Santander city (a) and in AIMSUN software (b)

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.

Removing on-street parking
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 1988 sections. The traffic demand for passenger cars, LGVs and HGVs are 23391 trips, 3141 trips and 16 trips, respectively. The network is presented in *Figure C.3.*

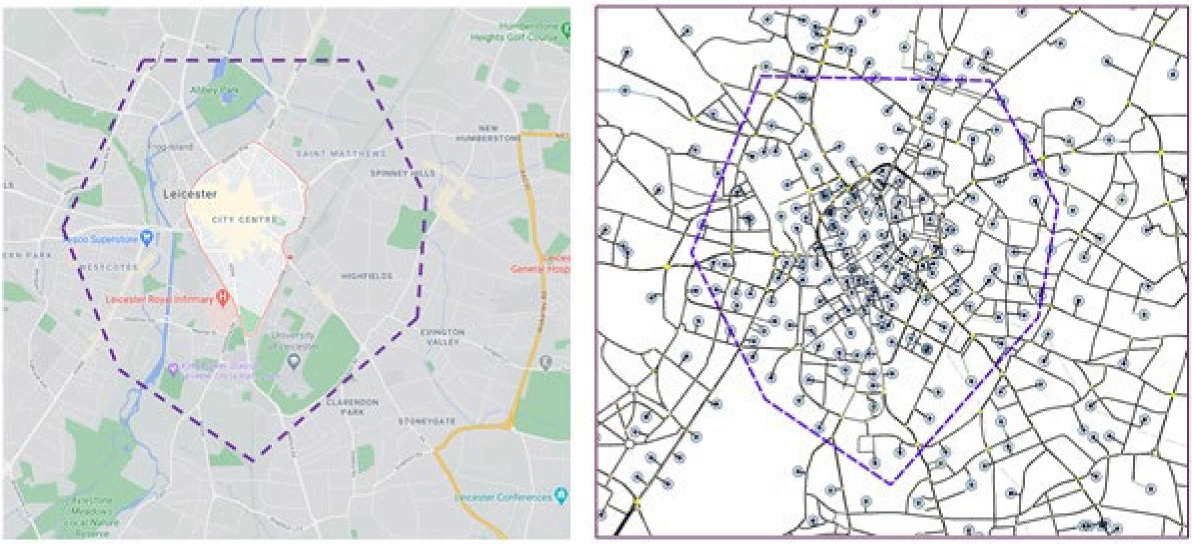


Figure C.3: The Leicester city centre network in AIMSUN software

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 C.4*.

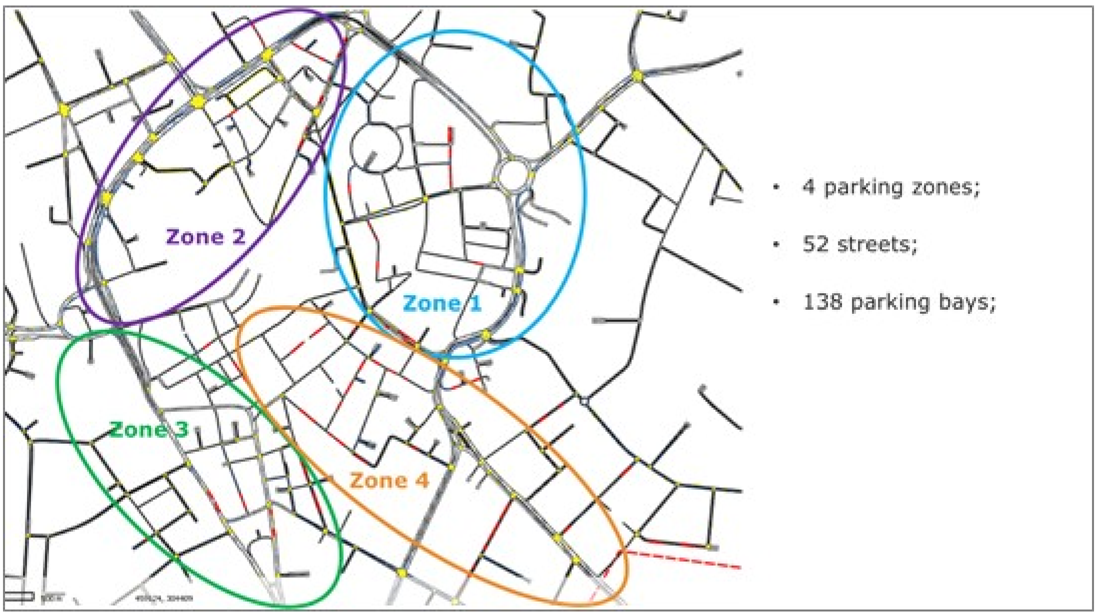


Figure C.4: On-street parking zones in AIMSUN software

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
- Cyclists are not modelled in the replacing on-street parking spaces with cycling lanes scenario due to the software limitation.

Automated ride sharing

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 C.5*), 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.

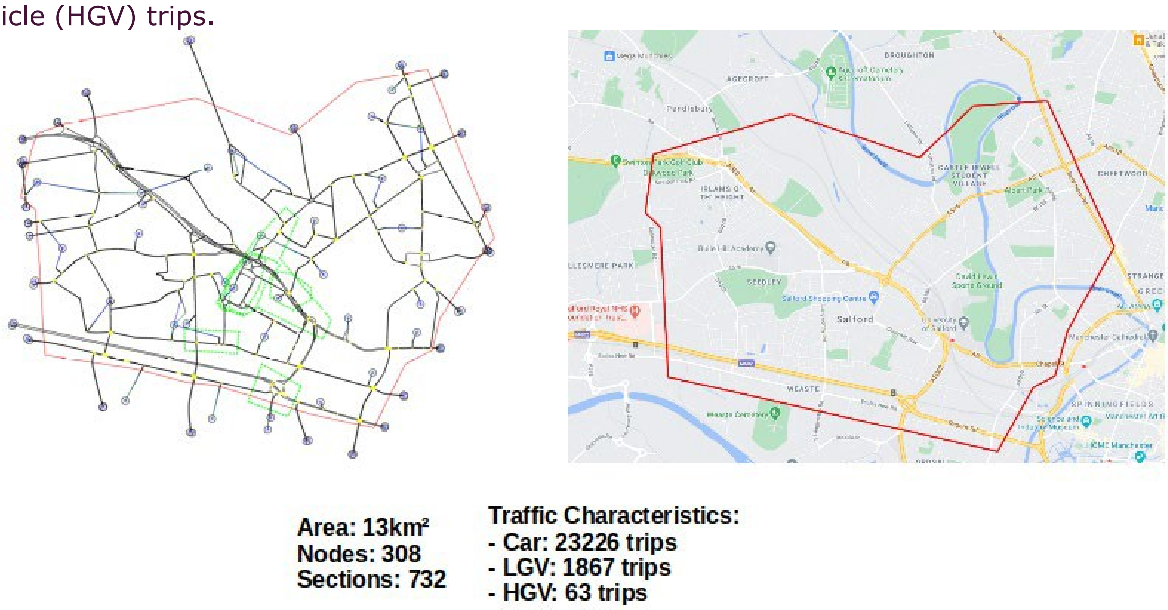


Figure C.5: The Manchester network in AIMSUN software

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. 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. 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.

As shown in *Figure C.6* eight clusters were determined by the algorithm, i.e., eight depots assigned to the nearest centroid from the exemplar of each cluster.

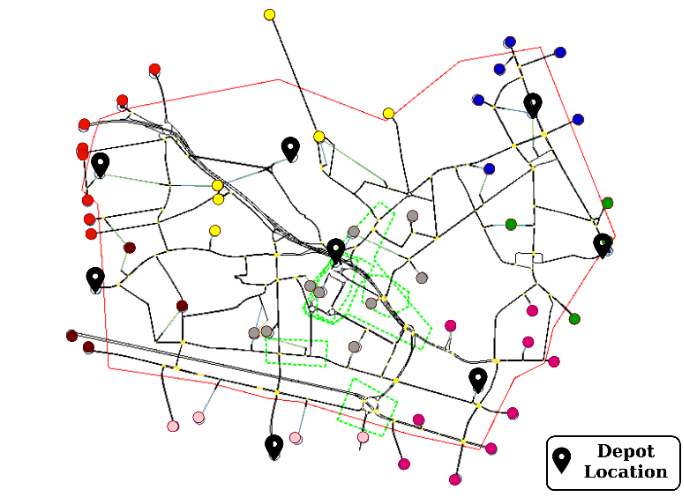


Figure C.6: Allocation of SAV service depots based on Affinity Propagation clustering algorithm

Table C.1 presents 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 C.1: 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)				

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 C.7)* 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.

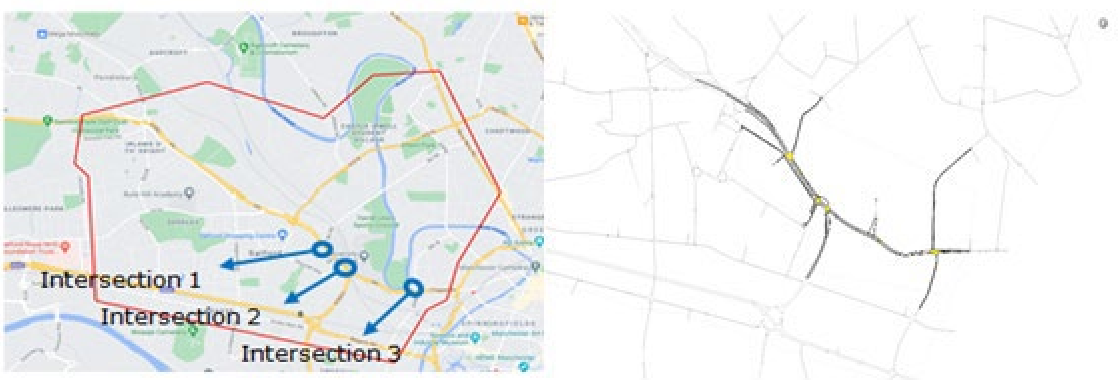


Figure C.7: Test corridor in Manchester network for GLOSA application

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 while upper limit was kept as speed limit +5mph.

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

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

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

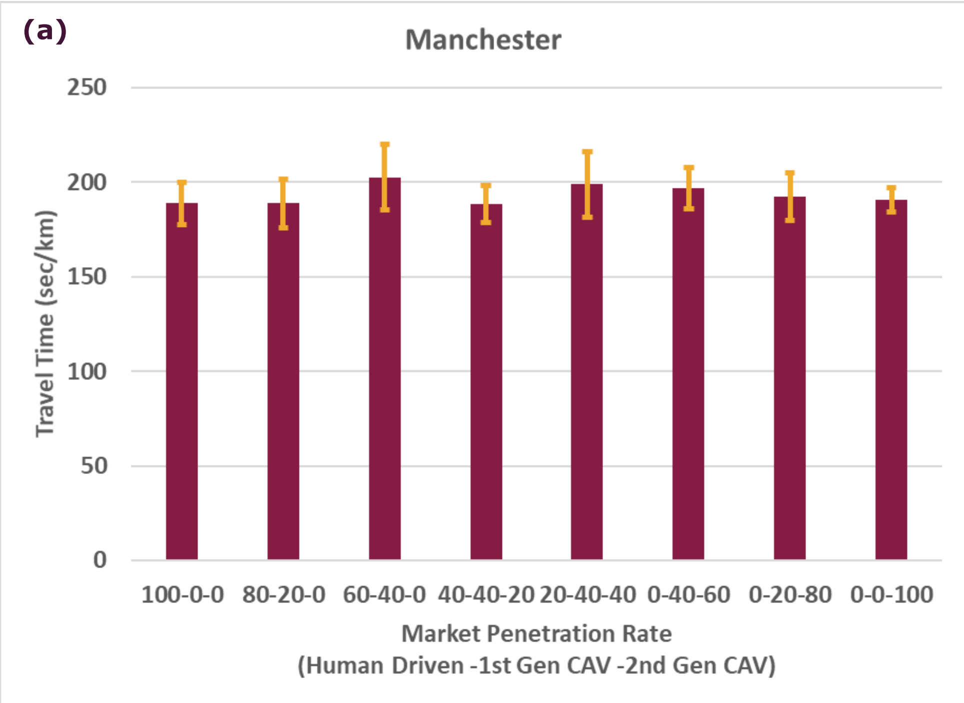
C.2 Microsimulation runs: standard deviation

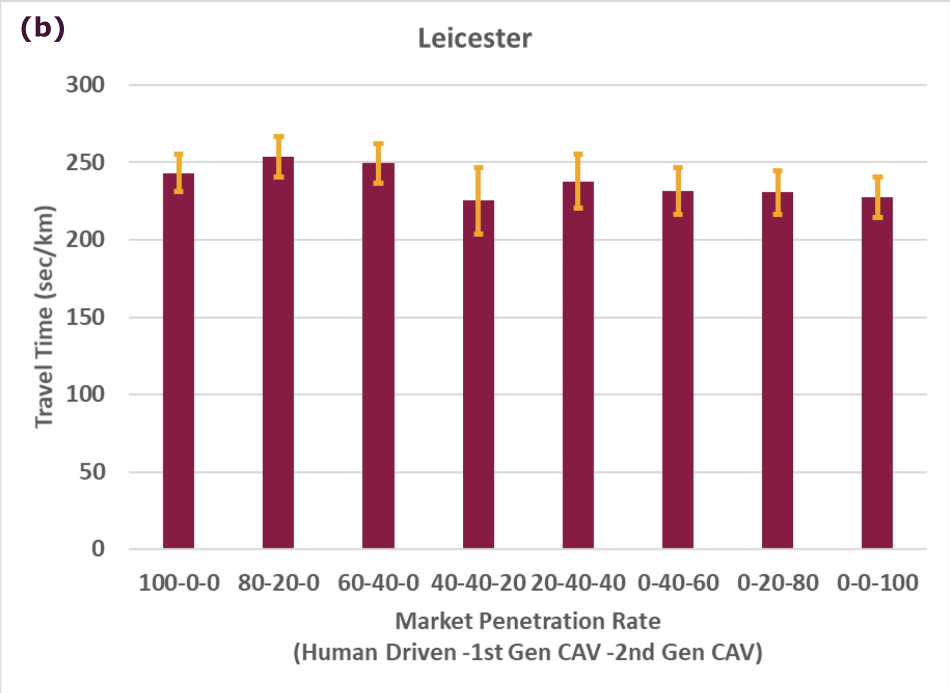
To estimate the microsimulation impacts, the simulation was run multiple times. From this, a standard deviation is available which indicates the amount of variation between simulation runs. This does not indicate the sensitivity of the simulation to different parameters, as parameters were kept constant for a given penetration rate scenario. It rather indicates the level of random variation in the model.

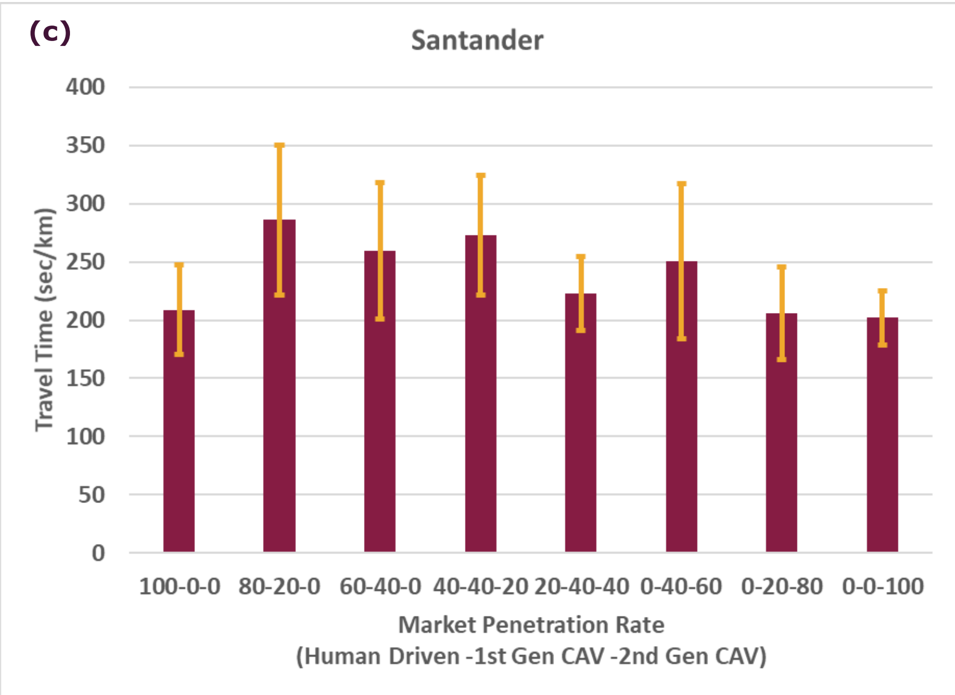
The standard deviation was calculated for three networks used in Work Package 6: Manchester, Leicester and Santander. Important to note is that this was calculated for entire networks, while each of the three SUCs calculated in Manchester used a different sub-section of the network and therefore used a smaller network. For these three networks, the baseline scenario (no sub-use case implementation) was calculated for the impacts on travel time, congestion, and total kilometres travelled. These results are shown in the graphs below.

As can be seen in the graphs below, the Santander network has especially high standard deviations. This can be explained due to the smaller size of the network, making small random variations in the traffic situations much more visible between simulation trials. It is likely that the smaller portions of the Manchester network used in SUC estimates likewise showed more variation compared to the larger network.

Travel time

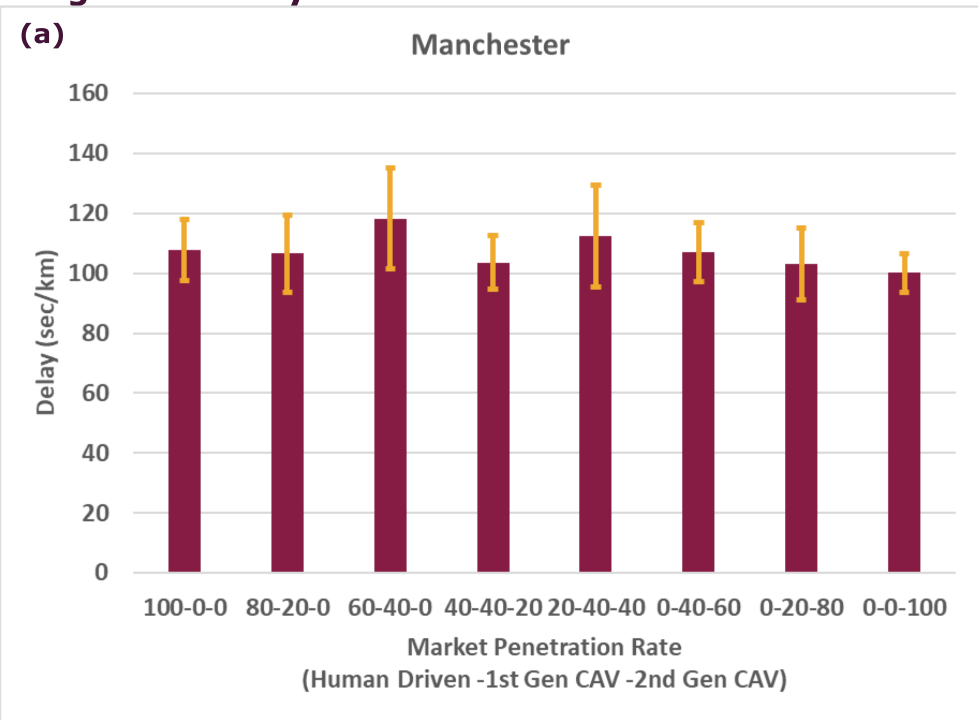


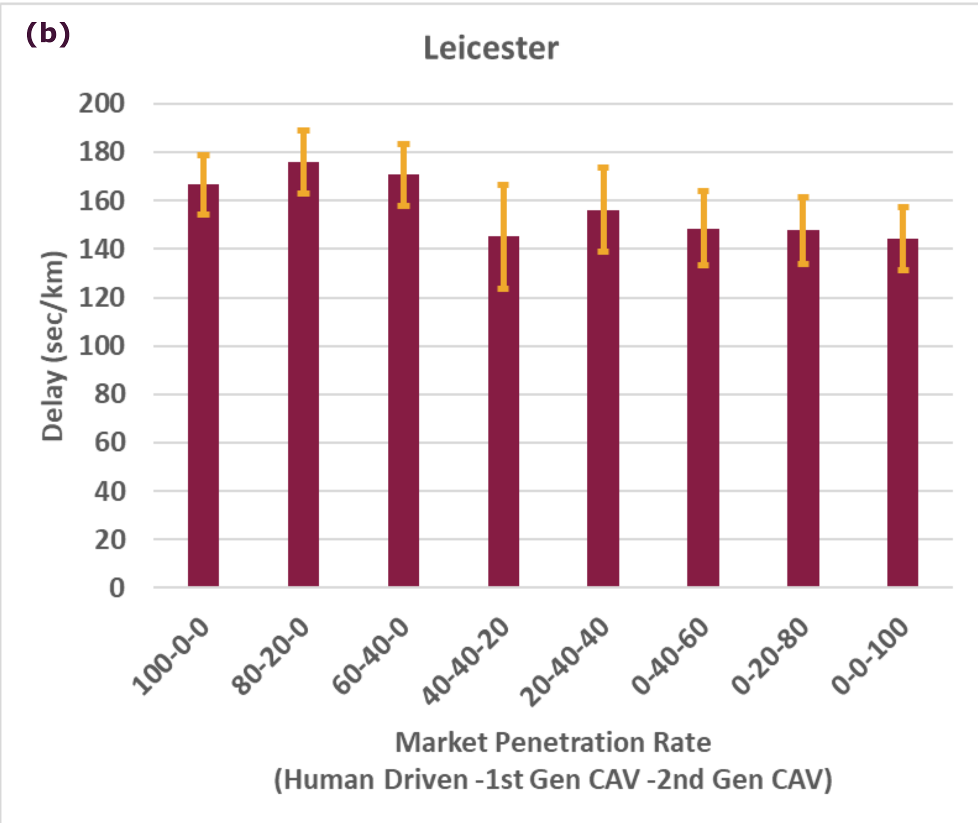


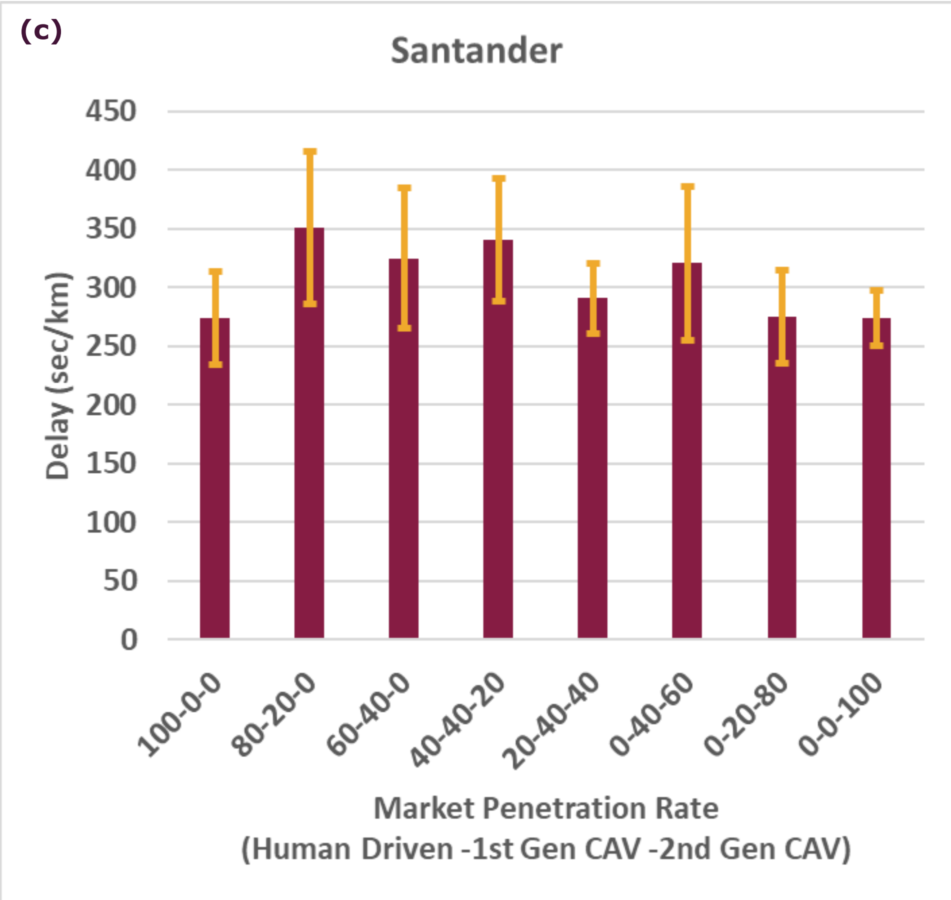


Figures C.8a-c: Baseline travel time development per network. Standard deviation indicated in orange.

Congestion delays

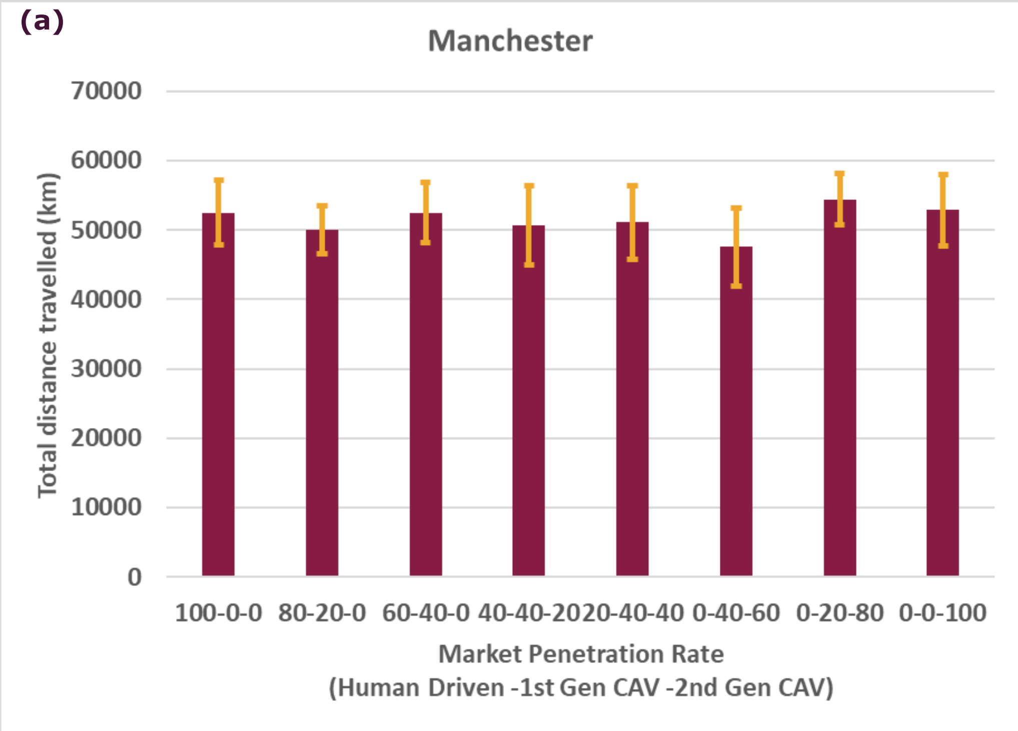


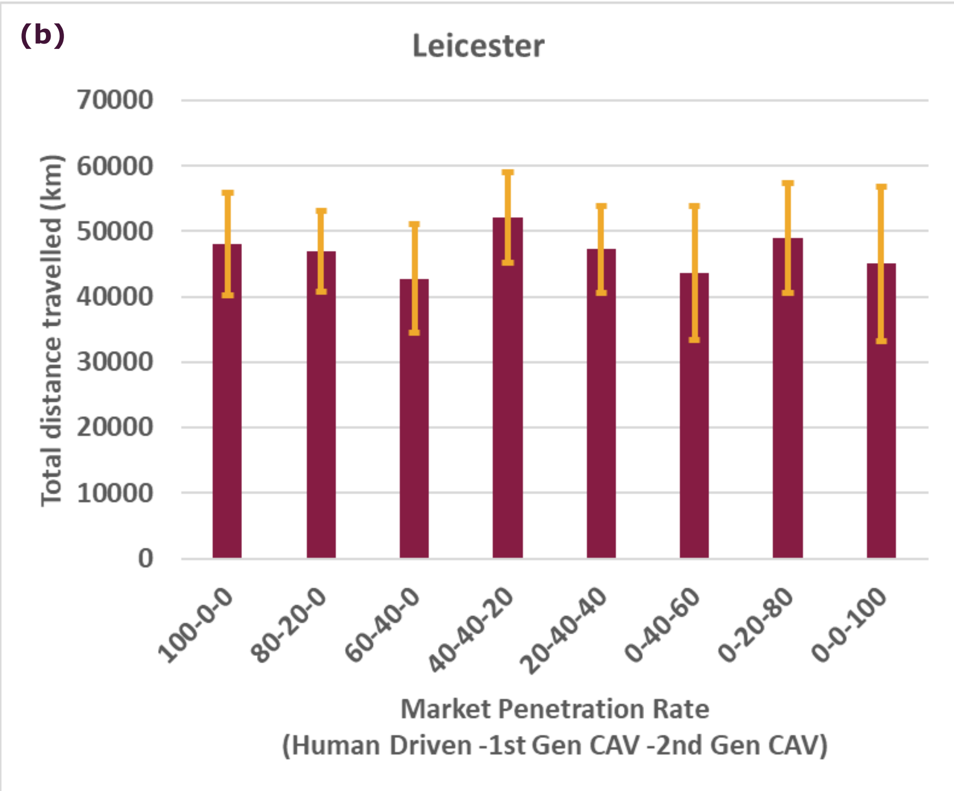


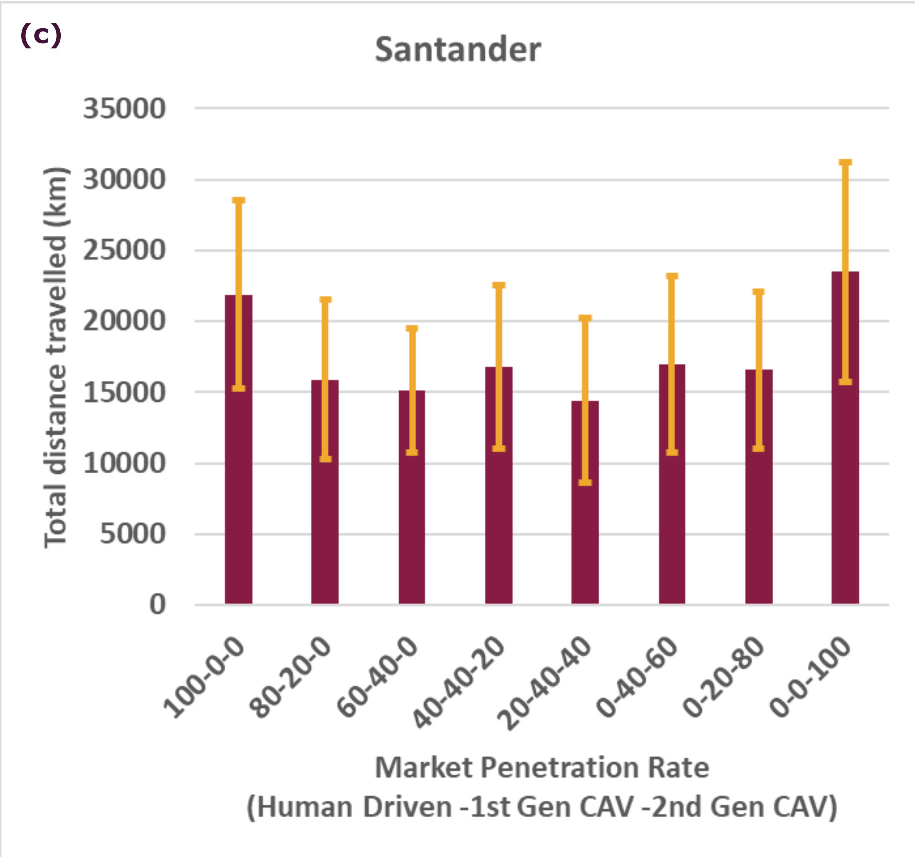


Figures C.9a-c: Baseline congestion delay development per network. Standard deviation indicated in orange.

Total kilometres travelled







Figures C.10a-c: Baseline total kilometres travelled development per network. Standard deviation indicated in orange.

Appendix D Full results

D.1 Environmental impacts

			Market penetration rate: AVs in Background vehicle fleet (Human-driven vehicle - 1st Generation AV - 2nd Generation AV)								
Impact	**Sub-use case**	**Scenario**	**100-0-0**	**80-20-0**	**60-40-0**	**40-40-20**	**20-40-40**	**0-40-60**	**0-20-80**	**0-0-100**	**Method**
Energy efficiency	Road use pricing	Baseline	0,0%	-1,9%	-3,8%	3,7%	9,9%	7,6%	7,6%	7,6%	Delphi (expert survey)
		Empty km pricing	-	6,9%	6,9%	6,9%	8,8%	8,8%	8,8%	8,8%	
		Static toll	-	7,5%	9,2%	9,2%	7,4%	5,6%	5,6%	5,6%	
		Dynamic toll	-	13,1%	13,1%	12,7%	12,7%	12,7%	12,7%	12,7%	
	Dedicated lanes for AVs	Baseline	0,0%	0,3%	-3,7%	0,3%	0,3%	4,9%	4,9%	4,9%	
		Outermost motorway lane	-	-3,7%	-5,7%	0,2%	3,8%	5,9%	5,9%	5,9%	
		Innermost motorway lane	-	0,2%	0,3%	5,5%	9,1%	9,1%	9,1%	9,1%	
		Outermost motorway lane and A-road	-	0,2%	-3,2%	5,5%	3,4%	5,5%	5,5%	5,5%	
		Dynamically controlled AV dedicated lane	-	4,2%	4,2%	6,4%	6,3%	6,3%	6,3%	6,3%	
	Parking price regulation	Baseline	0,0%	6,0%	14,0%	23,1%	25,4%	30,6%	30,6%	30,6%	
		Park inside	-	7,9%	11,6%	22,5%	24,5%	26,8%	26,8%	26,8%	
		Return to origin	-	-2,0%	3,7%	6,1%	12,7%	15,0%	15,0%	15,0%	
		Drive around	-	-0,4%	-0,4%	-5,9%	-10,1%	-13,8%	-13,8%	-13,8%	
		Park outside	-	3,6%	3,6%	9,3%	7,5%	13,2%	13,2%	13,2%	
	Replacing on-street parking	Baseline	0,0%	0,3%	4,4%	11,3%	12,5%	12,9%	12,9%	12,9%	
		Space for public use	-	6,8%	8,8%	10,8%	10,8%	13,3%	13,3%	13,3%	
		Driving lanes	-	-3,7%	-3,8%	-6,1%	-2,1%	-2,7%	-2,7%	-2,7%	
		Pick-up/drop-off	-	-10,2%	-3,8%	-3,6%	-2,6%	-7,1%	-7,1%	-7,1%	
	Automated ride sharing	Baseline	0,0%	9,8%	10,3%	11,1%	14,2%	14,2%	14,2%	14,2%	
		Automated ridesharing	-	6,3%	9,8%	13,8%	20,0%	20,0%	20,0%	20,0%	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0%	9,8%	10,3%	11,1%	14,2%	14,2%	14,2%	14,2%	
		GLOSA	-	9,4%	14,8%	18,7%	27,9%	27,9%	27,9%	27,9%	
CO2 emissions	Dedicated lanes for AVs	Baseline	0,0%	-20,2%	-47,7%	-76,3%	-88,0%	-100,0%	-100,0%	-100,0%	Micro-simulation (Manchester)
		Motorway and A road	-	-22,8%	-49,3%	-76,3%	-88,4%	-	-	-	
		A road right most lane	-	-23,7%	-49,4%	-76,6%	-88,5%	-	-	-	
		A road left most lane	-	-20,4%	-49,0%	-76,9%	-88,3%	-	-	-	
		Motorway only	-	-20,8%	-48,7%	-76,2%	-88,2%	-	-	-	
	Parking price regulation	Baseline	0,0%	-19,3%	-38,8%	-59,0%	-79,2%	-98,8%	-98,9%	-98,9%	
		Drive Around	-	-18,8%	-42,1%	-61,3%	-79,8%	-99,0%	-99,0%	-99,0%	

		Balanced	-	-17,8%	-40,0%	-58,6%	-78,5%	-98,8%	-98,8%	-98,8%	Micro-simulation (Santander)
		Heavy Return to Origin and Park Outside	-	-18,5%	-39,0%	-58,8%	-78,8%	-98,8%	-98,8%	-98,8%	
	Replacing on-street parking	Baseline	0,0%	-19,6%	-49,5%	-77,4%	-87,5%	-97,6%	-97,4%	-97,5%	Micro-simulation (Leicester)
		Removing half of the on-street parking spaces	-5,6%	-24,7%	-51,2%	-78,6%	-88,2%	-97,6%	-97,7%	-97,4%	
		Replacing with driving lanes	-13,3%	-30,6%	-56,2%	-81,0%	-89,2%	-97,2%	-97,2%	-97,2%	
		Replacing with pick-up and/or drop-off points	-9,7%	-24,8%	-52,7%	-79,3%	-88,7%	-97,5%	-97,6%	-97,5%	
		Replacing with public spaces	-13,0%	-29,7%	-55,5%	-80,9%	-89,0%	-97,2%	-97,2%	-97,2%	
		Replacing with cycling lanes	-11,7%	-30,3%	-55,5%	-81,0%	-89,1%	-97,3%	-97,2%	-97,2%	
	Automated ride sharing	Baseline	0,0%	-20,9%	-49,8%	-77,0%	-88,6%	-100,0%	-100,0%	-100,0%	Micro-simulation (Manchester)
		5% demand served - 20% willingness to share	-	-18,0%	-47,9%	-76,7%	-88,2%	-100,0%	-100,0%	-100,0%	
		5% demand served - 50% willingness to share	-	-17,9%	-49,4%	-76,7%	-88,5%	-100,0%	-100,0%	-100,0%	
		5% demand served - 80% willingness to share	-	-19,7%	-48,6%	-76,7%	-88,5%	-100,0%	-100,0%	-100,0%	
		5% demand served - 100% willingness to share	-	-19,8%	-48,3%	-76,9%	-88,5%	-100,0%	-100,0%	-100,0%	
		10% demand served - 20% willingness to share	-	-18,4%	-47,8%	-75,7%	-88,1%	-100,0%	-100,0%	-100,0%	
		10% demand served - 50% willingness to share	-	-17,0%	-48,0%	-75,6%	-88,2%	-100,0%	-100,0%	-100,0%	
		10% demand served - 80% willingness to share	-	-19,2%	-47,5%	-75,8%	-88,2%	-100,0%	-100,0%	-100,0%	
		10% demand served - 100% willingness to share	-	-18,4%	-47,6%	-76,1%	-88,2%	-100,0%	-100,0%	-100,0%	
		20% demand served - 20% willingness to share	-	-22,0%	-49,9%	-77,1%	-88,6%	-100,0%	-100,0%	-100,0%	
		20% demand served - 50% willingness to share	-	-22,3%	-50,1%	-76,7%	-88,4%	-100,0%	-100,0%	-100,0%	
		20% demand served - 80% willingness to share	-	-20,4%	-48,6%	-76,4%	-88,3%	-100,0%	-100,0%	-100,0%	
		20% demand served - 100% willingness to share	-	-19,4%	-47,8%	-75,8%	-88,0%	-100,0%	-100,0%	-100,0%	
	Green Light Optimised Speed Advisory (GLOSA)	Baseline	0,0%	-20,7%	-48,8%	-76,9%	-88,6%	-100,0%	-100,0%	-100,0%	Micro-simulation (Manchester)
		GLOSA on 1 Intersection	0,0%	-20,7%	-48,8%	-76,8%	-88,6%	-100,0%	-100,0%	-100,0%	
		GLOSA on 2 Intersections	0,0%	-20,9%	-48,7%	-76,9%	-88,6%	-100,0%	-100,0%	-100,0%	
		GLOSA on 3 Intersections	0,0%	-20,8%	-48,7%	-76,9%	-88,6%	-100,0%	-100,0%	-100,0%	

D.2 Mobility impacts

Impact	Sub-use case	Scenario	Market penetration rate: AVs in Background vehicle fleet (Human-driven vehicle - 1st Generation AV - 2nd Generation AV)								Method
			100-0-0	80-20-0	60-40-0	40-40-20	20-40-40	0-40-60	0-20-80	0-0-100	
Travel time	Dedicated lanes for CAVs	Baseline	0%	0%	7%	0%	5%	4%	2%	1%	Micro-simulation (Manchester)
		Motorway and A road (fixed)	-	3%	3%	5%	3%	-	-	-	
		A road right most lane (fixed)	-	1%	-1%	3%	2%	-	-	-	
		A road left most lane (fixed)	-	-3%	-4%	-3%	2%	-	-	-	
		Motorway only (fixed)	-	5%	5%	6%	5%	-	-	-	
	Parking price regulation	Baseline	0%	28%	19%	24%	6%	17%	0%	0%	Micro-simulation (Santander)
		Drive around without parking	-	20%	18%	25%	31%	25%	18%	25%	
		Balanced scenario: park inside centre (13%), return to origin (22%), outside centre (45%), or drive around (20%)	-	16%	20%	16%	14%	26%	19%	23%	
		Return to Origin (33%) or Park Outside centre (67%)	-	17%	22%	21%	27%	18%	23%	30%	
	Replacing on-street parking	Baseline	0%	4%	3%	-7%	-2%	-5%	-5%	-7%	Micro-simulation (Leicester)
		Removing half of the on-street parking spaces	-3%	-7%	-6%	-11%	-12%	-13%	-8%	-11%	
		Replacing with driving lanes	-31%	-31%	-33%	-36%	-35%	-34%	-34%	-34%	
		Replacing with pick-up and/or drop-off points	-9%	-10%	-14%	-18%	-15%	-15%	-16%	-17%	
		Replacing with public spaces	-30%	-29%	-30%	-34%	-32%	-32%	-32%	-33%	
		Replacing with cycling lanes	-28%	-30%	-30%	-34%	-34%	-32%	-33%	-32%	
	Automated ride sharing	Baseline	0%	-1%	-3%	-5%	-3%	1%	-2%	-2%	Micro-simulation (Manchester)
		5% demand served - 20% willingness to share	-	11%	11%	11%	6%	10%	4%	3%	
		5% demand served - 50% willingness to share	-	9%	8%	8%	7%	7%	8%	4%	
		5% demand served - 80% willingness to share	-	6%	6%	1%	-3%	8%	8%	1%	
		5% demand served - 100% willingness to share	-	2%	4%	-1%	0%	3%	6%	0%	
		10% demand served - 20% willingness to share	-	17%	12%	14%	16%	18%	17%	11%	
		10% demand served - 50% willingness to share	-	17%	11%	16%	9%	13%	11%	11%	
		10% demand served - 80% willingness to share	-	12%	12%	9%	5%	10%	5%	3%	
		10% demand served - 100% willingness to share	-	13%	11%	8%	5%	4%	5%	0%	
		20% demand served - 20% willingness to share	-	8%	6%	6%	11%	13%	14%	13%	
		20% demand served - 50% willingness to share	-	4%	5%	5%	6%	10%	7%	8%	
		20% demand served - 80% willingness to share	-	5%	6%	3%	2%	6%	6%	4%	
		20% demand served - 100% willingness to share	-	4%	7%	5%	2%	4%	3%	-2%	
	Green Light Optimised Speed Advisory	Baseline	0%	0%	0%	0%	1%	2%	4%	4%	Micro-simulation (Manchester)
		GLOSA on 1 Intersection	0%	0%	0%	0%	0%	1%	3%	2%	
		GLOSA on 2 Intersections	0%	0%	0%	-1%	0%	1%	2%	2%	
		GLOSA on 3 Intersections	0%	0%	-1%	-1%	0%	0%	2%	2%	
Average travel time (5km trip)	Baseline	0 euro	0%	0%	0%	0%	0%	-1%	0%	-1%	Meso-simulation (Vienna)
	Road-use pricing	Static toll: 5 euros (to enter Vienna)	1%	1%	1%	1%	1%	1%	1%	1%	
		Static toll: 10 euros (to enter Vienna)	2%	2%	2%	2%	2%	2%	2%	2%	
		Static toll: 100 euros (to enter Vienna)	4%	4%	4%	4%	4%	3%	4%	3%	

		Dynamic toll: €0,7/km (€5 to cross Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Dynamic toll: €1,4/km (€10 to cross Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Dynamic toll: €14/km (€100 to cross Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
Access to travel	Road use pricing	Baseline	0%	-2%	0%	4%	13%	23%	23%	23%	Delphi (expert survey)
		Empty km pricing	-	-8%	-4%	-3%	-4%	1%	1%	1%	
		Static toll	-	-8%	-8%	-4%	-2%	-2%	-2%	-2%	
		Dynamic toll	-	-8%	-8%	-4%	0%	4%	4%	4%	
	Dedicated lanes for CAVs	Baseline	0%	4%	4%	16%	24%	27%	27%	27%	
		Outermost motorway lane	-	6%	2%	6%	6%	8%	8%	8%	
		Innermost motorway lane	-	4%	1%	7%	4%	7%	7%	7%	
		Outermost motorway lane and A-road	-	7%	4%	12%	7%	15%	15%	15%	
		Dynamically controlled AV dedicated lane	-	7%	12%	12%	12%	17%	17%	17%	
	Parking price regulation	Baseline	0%	2%	12%	22%	36%	51%	51%	51%	
		Park inside	-	10%	16%	18%	27%	33%	33%	33%	
		Return to origin	-	6%	8%	18%	22%	30%	30%	30%	
		Drive around	-	6%	12%	14%	27%	28%	28%	28%	
		Park outside	-	2%	-1%	4%	4%	9%	9%	9%	
	Replacing on-street parking	Baseline	0%	-9%	-9%	-11%	-9%	-11%	-11%	-11%	
		Space for public use	-	-7%	-6%	-8%	-11%	-16%	-16%	-16%	
		Driving lanes	-	-6%	-6%	0%	7%	7%	7%	7%	
		Pick-up/drop-off	-	-1%	0%	0%	0%	1%	1%	1%	
	Automated ride sharing	Baseline	0%	13%	16%	23%	23%	26%	26%	26%	
		Automated ridesharing	-	11%	17%	29%	32%	41%	41%	41%	
	Green Light Optimised Speed Advisory	Baseline	0%	13%	16%	23%	23%	26%	26%	26%	
		GLOSA	-	3%	3%	3%	0%	0%	0%	0%	
Total kilometres travelled (vehicle km)	Dedicated lanes for CAVs	Baseline	0%	-5%	0%	-4%	-3%	-9%	4%	1%	Micro-simulation (Manchester)
		Motorway and A road (fixed)	-	-2%	-3%	2%	-10%	-	-	-	
		A road right most lane (fixed)	-	-8%	0%	0%	-14%	-	-	-	
		A road left most lane (fixed)	-	4%	4%	1%	-3%	-	-	-	
		Motorway only (fixed)	-	2%	-4%	0%	-6%	-	-	-	
	Parking price regulation	Baseline	0%	-27%	-31%	-23%	-34%	-23%	-24%	7%	Micro-simulation (Santander)
		Drive around without parking	-	-14%	-44%	-38%	-51%	-68%	-70%	-69%	
		Balanced scenario: park inside centre (13%), return to origin (22%), outside centre (45%), or drive around (20%)	-	-32%	-42%	-29%	-39%	-33%	-27%	-21%	
		Return to Origin (33%) or Park Outside centre (67%)	-	-26%	-42%	-40%	-45%	-33%	-28%	4%	
	Replacing on-street parking	Baseline	0%	-2%	-11%	9%	-2%	-9%	2%	-6%	Micro-simulation (Leicester)
		Removing half of the on-street parking spaces	-9%	-6%	-7%	-7%	-5%	-5%	-9%	2%	
		Replacing with driving lanes	11%	11%	9%	12%	11%	12%	12%	13%	
		Replacing with pick-up and/or drop-off points	-15%	-1%	-6%	-3%	-17%	-3%	-7%	-2%	
		Replacing with public spaces	10%	11%	9%	11%	10%	12%	12%	12%	
		Replacing with cycling lanes	11%	11%	10%	9%	12%	8%	12%	12%	
	Automated ride sharing	Baseline	0%	-6%	-13%	-8%	-6%	-5%	-10%	-8%	Micro-simulation (Manchester)
		5% demand served - 20% willingness to share	-	-3%	-12%	-12%	-13%	-13%	-14%	-9%	
		5% demand served - 50% willingness to share	-	-3%	-17%	-10%	-11%	-14%	-8%	-9%	

		5% demand served - 80% willingness to share	-	-6%	-12%	-7%	-10%	-11%	-13%	-4%	
		5% demand served - 100% willingness to share	-	-6%	-7%	-11%	-12%	-11%	-10%	-2%	
		10% demand served - 20% willingness to share	-	-11%	-14%	-15%	-10%	-14%	-11%	-10%	
		10% demand served - 50% willingness to share	-	-8%	-13%	-11%	-9%	-5%	-10%	-5%	
		10% demand served - 80% willingness to share	-	-11%	-10%	-2%	-5%	-4%	-6%	1%	
		10% demand served - 100% willingness to share	-	-8%	-11%	-4%	-2%	-6%	-4%	0%	
		20% demand served - 20% willingness to share	-	-7%	-12%	-14%	-19%	-17%	-13%	-9%	
		20% demand served - 50% willingness to share	-	-7%	-11%	-4%	-11%	-9%	-6%	-1%	
		20% demand served - 80% willingness to share	-	-5%	-8%	-5%	-5%	-11%	-5%	5%	
		20% demand served - 100% willingness to share	-	-11%	-9%	-7%	-2%	-1%	0%	4%	
	Green Light Optimised Speed Advisory	Baseline	0%	0%	0%	0%	-1%	0%	-2%	-1%	Micro-simulation (Manchester)
		GLOSA on 1 Intersection	0%	0%	0%	0%	-1%	0%	-2%	-1%	
		GLOSA on 2 Intersections	0%	0%	0%	0%	-1%	0%	-1%	-1%	
		GLOSA on 3 Intersections	0%	0%	0%	0%	-1%	0%	-1%	-1%	
Amount of travel per person	Baseline	0 euro	0%	0%	0%	0%	0%	0%	0%	0%	Meso-simulation (Vienna)
	Road-use pricing	Static toll: 5 euros (to enter Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Static toll: 10 euros (to enter Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Static toll: 100 euros (to enter Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Dynamic toll: €0,7/km (€5 to cross Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Dynamic toll: €1,4/km (€10 to cross Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
		Dynamic toll: €14/km (€100 to cross Vienna)	0%	0%	0%	0%	0%	0%	0%	0%	
Congestion (sec/km)	Dedicated lanes for CAVs	Baseline	0%	-1%	10%	-4%	4%	-1%	-4%	-7%	Micro-simulation (Manchester)
		Motorway and A road (fixed)	-	2%	3%	3%	-1%	-	-	-	
		A road right most lane (fixed)	-	0%	-6%	0%	-2%	-	-	-	
		A road left most lane (fixed)	-	-5%	-9%	-9%	-2%	-	-	-	
		Motorway only (fixed)	-	6%	5%	6%	2%	-	-	-	
	Parking price regulation	Baseline	0%	37%	24%	31%	7%	20%	-1%	-3%	Micro-simulation (Santander)
		Drive around without parking	-	26%	25%	33%	41%	35%	26%	34%	
		Balanced scenario: park inside centre (13%), return to origin (22%), outside centre (45%), or drive around (20%)	-	22%	26%	21%	18%	33%	24%	29%	
		Return to Origin (33%) or Park Outside centre (67%)	-	22%	29%	28%	35%	23%	28%	30%	
	Replacing on-street parking	Baseline	0%	6%	2%	-13%	-6%	-11%	-11%	-13%	Micro-simulation (Leicester)
		Removing half of the on-street parking spaces	-5%	-11%	-11%	-18%	-21%	-23%	-16%	-20%	
		Replacing with driving lanes	-45%	-46%	-49%	-54%	-54%	-54%	-54%	-54%	
		Replacing with pick-up and/or drop-off points	-13%	-15%	-21%	-28%	-25%	-26%	-27%	-28%	
		Replacing with public spaces	-43%	-43%	-45%	-52%	-50%	-51%	-50%	-52%	
		Replacing with cycling lanes	-41%	-44%	-46%	-52%	-52%	-51%	-51%	-51%	
	Automated ride sharing	Baseline	0%	-3%	-7%	-12%	-10%	-4%	-10%	-11%	Micro-simulation (Manchester)
		5% demand served - 20% willingness to share	-	19%	17%	15%	6%	10%	-1%	-2%	
		5% demand served - 50% willingness to share	-	14%	11%	10%	7%	5%	6%	-1%	
		5% demand served - 80% willingness to share	-	10%	9%	-1%	-9%	7%	6%	-5%	
		5% demand served - 100% willingness to share	-	2%	6%	-5%	-5%	-1%	3%	-8%	

		10% demand served - 20% willingness to share	-	28%	18%	20%	22%	24%	22%	11%	
		10% demand served - 50% willingness to share	-	28%	17%	23%	10%	16%	11%	11%	
		10% demand served - 80% willingness to share	-	19%	19%	12%	5%	10%	3%	-1%	
		10% demand served - 100% willingness to share	-	21%	17%	11%	3%	0%	3%	-7%	
		20% demand served - 20% willingness to share	-	13%	8%	7%	13%	16%	18%	15%	
		20% demand served - 50% willingness to share	-	6%	6%	5%	6%	11%	5%	6%	
		20% demand served - 80% willingness to share	-	8%	8%	1%	-2%	4%	4%	1%	
		20% demand served - 100% willingness to share	-	5%	8%	5%	-2%	1%	-2%	-9%	
	Green Light Optimised Speed Advisory	Baseline	0%	-1%	-5%	-6%	-6%	-6%	-3%	-2%	Micro-simulation (Manchester)
		GLOSA on 1 Intersection	0%	-1%	-6%	-7%	-8%	-9%	-5%	-5%	
		GLOSA on 2 Intersections	0%	-2%	-5%	-8%	-9%	-10%	-6%	-5%	
		GLOSA on 3 Intersections	0%	-2%	-6%	-9%	-9%	-11%	-6%	-7%	
Modal split Vienna: Active modes (Walking & Cycling)	Baseline	no policy intervention	16%	16%	15%	13%	11%	7%			System dynamics
	Road use pricing	Static toll: 10 euros	18%	18%	17%	16%	15%	13%			
	Parking price regulation	Adjusted parking behaviour (Balanced scenario)	19%	19%	18%	18%	16%	11%			
	Replacing on-street parking	Removing half of spaces	18%	17%	16%	14%	11%	7%			
		Replacing with driving lanes	19%	18%	18%	16%	14%	10%			
	Automated ride sharing	20% of demand & 100% willing to share	15%	14%	13%	11%	9%	6%			
Modal split Vienna: Public transport	Baseline	no policy intervention	48%	48%	47%	45%	43%	40%			
	Road use pricing	Static toll: 10 euros	57%	57%	55%	53%	52%	47%			
	Parking price regulation	Adjusted parking behaviour (Balanced scenario)	46%	45%	43%	41%	39%	42%			
	Replacing on-street parking	Removing half of spaces	48%	47%	45%	43%	42%	39%			
		Replacing with driving lanes	44%	43%	38%	34%	31%	30%			
	Automated ride sharing	20% of demand & 100% willing to share	55%	55%	53%	51%	50%	47%			
Modal split: Active modes (Walking & cycling)	Road use pricing	Baseline	0%	-6%	-6%	-12%	-20%	-20%			Delphi (expert survey)
		Empty km pricing	-	4%	6%	10%	6%	4%			
		Static toll	-	11%	15%	15%	13%	13%			
		Dynamic toll	-	-6%	-6%	0%	0%	3%			
	Dedicated lanes for CAVs	Baseline	0%	-5%	-5%	-9%	-9%	-13%			
		Outermost motorway lane	-	-3%	0%	-5%	-3%	-9%			
		Innermost motorway lane	-	0%	-3%	-5%	-8%	-9%			
		Outermost motorway lane and A-road	-	0%	-3%	-5%	-5%	-5%			
		Dynamically controlled AV dedicated lane	-	0%	-3%	-3%	-3%	-4%			
	Parking price regulation	Baseline	0%	-13%	-17%	-28%	-30%	-35%			
		Park inside	-	-6%	-10%	-12%	-17%	-14%			
		Return to origin	-	-6%	-8%	-4%	-6%	-12%			
		Drive around	-	-8%	-8%	-12%	-17%	-21%			
		Park outside	-	-2%	-2%	3%	2%	3%			
	Replacing on-street parking	Baseline	0%	-6%	-10%	-16%	-21%	-28%			
		Space for public use	-	7%	9%	18%	27%	32%			
		Driving lanes	-	9%	9%	7%	9%	9%			

		Pick-up/drop-off	-	-2%	-1%	3%	3%	8%			
	Automated ride sharing	Baseline	0%	2%	3%	7%	12%	3%			
		Automated ridesharing	-	7%	8%	7%	3%	3%			
	Green Light Optimised Speed Advisory	Baseline	0%	2%	3%	7%	12%	3%			
		GLOSA	-	-3%	-5%	-5%	-5%	-5%			
Modal split: Public transport	Road use pricing	Baseline	0%	-8%	-10%	-16%	-26%	-29%			Delphi (expert survey)
		Empty km pricing	-	6%	8%	5%	4%	4%			
		Static toll	-	17%	21%	15%	13%	16%			
		Dynamic toll	-	14%	15%	9%	8%	8%			
	Dedicated lanes for CAVs	Baseline	0%	-4%	-4%	-12%	-20%	-25%			
		Outermost motorway lane	-	-5%	-3%	-12%	-12%	-18%			
		Innermost motorway lane	-	-5%	-3%	-8%	-12%	-18%			
		Outermost motorway lane and A-road	-	-3%	-5%	-12%	-17%	-18%			
		Dynamically controlled AV dedicated lane	-	-3%	-5%	-8%	-14%	-16%			
	Parking price regulation	Baseline	0%	-7%	-10%	-10%	-15%	-18%			
		Park inside	-	-7%	-8%	-13%	-17%	-15%			
		Return to origin	-	-5%	-8%	-5%	-12%	-15%			
		Drive around	-	-8%	-8%	-8%	-12%	-15%			
		Park outside	-	-2%	0%	8%	4%	7%			
	Replacing on-street parking	Baseline	0%	-8%	-10%	-8%	-12%	-10%			
		Space for public use	-	4%	8%	17%	20%	27%			
		Driving lanes	-	8%	8%	5%	1%	2%			
		Pick-up/drop-off	-	-4%	-11%	-5%	4%	7%			
	Automated ride sharing	Baseline	0%	-1%	3%	-6%	-18%	-18%			
		Automated ridesharing	-	7%	7%	3%	-1%	-7%			
	Green Light Optimised Speed Advisory	Baseline	0%	-1%	3%	-6%	-18%	-18%			
		GLOSA	-	-5%	-5%	-5%	-5%	-8%			
Shared mobility rate	Road use pricing	Baseline	0%	-1%	6%	14%	17%	23%	23%	23%	Delphi (expert survey)
		Empty km pricing	-	5%	7%	13%	17%	21%	21%	21%	
		Static toll	-	11%	13%	15%	15%	17%	17%	17%	
		Dynamic toll	-	12%	14%	18%	22%	24%	24%	24%	
	Dedicated lanes for CAVs	Baseline	0%	4%	10%	19%	31%	36%	36%	36%	
		Outermost motorway lane	-	4%	0%	10%	10%	19%	19%	19%	
		Innermost motorway lane	-	4%	0%	10%	19%	21%	21%	21%	
		Outermost motorway lane and A-road	-	4%	0%	10%	10%	21%	21%	21%	
		Dynamically controlled AV dedicated lane	-	4%	0%	14%	13%	22%	22%	22%	
	Parking price regulation	Baseline	0%	-4%	2%	14%	18%	27%	27%	27%	
		Park inside	-	4%	10%	16%	26%	29%	29%	29%	
		Return to origin	-	4%	6%	12%	23%	20%	20%	20%	
		Drive around	-	2%	8%	19%	19%	30%	30%	30%	
		Park outside	-	4%	6%	22%	12%	16%	16%	16%	
	Replacing on-street parking	Baseline	0%	-6%	-2%	-4%	2%	11%	11%	11%	
		Space for public use	-	0%	13%	22%	42%	47%	47%	47%	
		Driving lanes	-	7%	4%	9%	8%	13%	13%	13%	

		Pick-up/drop-off	-	2%	1%	8%	17%	19%	19%	19%	
	Automated ride sharing	Baseline	0%	4%	7%	17%	27%	40%	40%	40%	
		Automated ridesharing	-	6%	15%	25%	36%	40%	40%	40%	
	Green Light Optimised Speed Advisory	Baseline	0%	4%	7%	17%	27%	40%	40%	40%	
		GLOSA	-	5%	8%	8%	12%	12%	12%	12%	
Vehicle utilisation rate	Road use pricing	Baseline	0%	3%	6%	22%	37%	46%	46%	46%	Delphi (expert survey)
		Empty km pricing	-	-1%	-1%	10%	12%	14%	14%	14%	
		Static toll	-	3%	7%	9%	13%	15%	15%	15%	
		Dynamic toll	-	-2%	2%	10%	18%	18%	18%	18%	
	Dedicated lanes for CAVs	Baseline	0%	4%	10%	36%	26%	29%	29%	29%	
		Outermost motorway lane	-	6%	4%	14%	25%	27%	27%	27%	
		Innermost motorway lane	-	4%	6%	10%	16%	19%	19%	19%	
		Outermost motorway lane and A-road	-	6%	4%	10%	10%	21%	21%	21%	
		Dynamically controlled AV dedicated lane	-	4%	0%	12%	9%	19%	19%	19%	
	Parking price regulation	Baseline	0%	3%	12%	23%	36%	50%	50%	50%	
		Park inside	-	2%	4%	12%	14%	18%	18%	18%	
		Return to origin	-	10%	14%	27%	35%	40%	40%	40%	
		Drive around	-	8%	14%	26%	31%	38%	38%	38%	
		Park outside	-	8%	10%	18%	25%	34%	34%	34%	
	Replacing on-street parking	Baseline	0%	3%	3%	6%	9%	19%	19%	19%	
		Space for public use	-	7%	8%	2%	0%	-1%	-1%	-1%	
		Driving lanes	-	5%	3%	3%	3%	5%	5%	5%	
		Pick-up/drop-off	-	-6%	-1%	4%	4%	2%	2%	2%	
	Automated ride sharing	Baseline	0%	6%	10%	19%	36%	43%	43%	43%	
		Automated ridesharing	-	8%	11%	17%	20%	20%	20%	20%	
	Green Light Optimised Speed Advisory	Baseline	0%	6%	10%	19%	36%	43%	43%	43%	
		GLOSA	-	5%	3%	5%	8%	8%	8%	8%	
Vehicle occupancy rate	Road use pricing	Baseline	0%	-5%	-5%	4%	2%	6%	6%	6%	Delphi (expert survey)
		Empty km pricing	-	8%	8%	12%	15%	17%	17%	17%	
		Static toll	-	10%	12%	18%	16%	18%	18%	18%	
		Dynamic toll	-	13%	15%	22%	22%	24%	24%	24%	
	Dedicated lanes for CAVs	Baseline	0%	1%	1%	-3%	-3%	1%	1%	1%	
		Outermost motorway lane	-	6%	4%	10%	10%	16%	16%	16%	
		Innermost motorway lane	-	4%	4%	6%	14%	16%	16%	16%	
		Outermost motorway lane and A-road	-	3%	3%	3%	0%	0%	0%	0%	
		Dynamically controlled AV dedicated lane	-	4%	4%	9%	9%	17%	17%	17%	
	Parking price regulation	Baseline	0%	4%	-2%	-2%	-3%	-5%	-5%	-5%	
		Park inside	-	4%	8%	8%	14%	23%	23%	23%	
		Return to origin	-	2%	4%	8%	8%	9%	9%	9%	
		Drive around	-	2%	-1%	-4%	-1%	4%	4%	4%	
		Park outside	-	4%	4%	11%	7%	17%	17%	17%	
	Replacing on-street parking	Baseline	0%	-6%	-6%	-8%	-9%	-9%	-9%	-9%	
		Space for public use	-	7%	9%	9%	19%	19%	19%	19%	
		Driving lanes	-	-6%	-8%	-4%	-2%	-10%	-10%	-10%	

		Pick-up/drop-off	-	-7%	-3%	-3%	9%	14%	14%	14%	
	Automated ride sharing	Baseline	0%	0%	0%	-4%	1%	10%	10%	10%	
		Automated ridesharing	-	9%	13%	20%	20%	20%	20%	20%	
	Green Light Optimised Speed Advisory	Baseline	0%	0%	0%	-4%	1%	10%	10%	10%	
		GLOSA	-	4%	4%	4%	4%	4%	4%	4%	

D.3 Societal, economic and safety impacts

			Market penetration rate: AVs in Background vehicle fleet (Human-driven vehicle - 1st Generation AV - 2nd Generation AV)								
Impact	**Sub-use case**	**Scenario**	**100-0-0**	**80-20-0**	**60-40-0**	**40-40-20**	**20-40-40**	**0-40-60**	**0-20-80**	**0-0-100**	**Method**
Vehicle operating cost	Road use pricing	Baseline	0,0%	6,1%	4,2%	4,3%	-5,5%	-7,4%	-7,4%	-7,4%	Delphi (expert survey)
		Empty km pricing	-	2,3%	2,3%	2,5%	-3,1%	-3,1%	-3,1%	-3,1%	
		Static toll	-	19,9%	19,4%	15,4%	9,3%	9,3%	9,3%	9,3%	
		Dynamic toll	-	17,3%	15,3%	14,9%	12,8%	13,3%	13,3%	13,3%	
	Dedicated lanes for AVs	Baseline	0,0%	11,7%	11,7%	4,8%	4,3%	0,2%	0,2%	0,2%	
		Outermost motorway lane	-	10,1%	4,3%	-5,6%	-10,1%	-14,0%	-14,0%	-14,0%	
		Innermost motorway lane	-	0,3%	0,3%	-3,6%	-10,1%	-10,1%	-10,1%	-10,1%	
		Outermost motorway lane and A-road	-	4,2%	0,3%	-3,6%	-8,1%	-10,1%	-10,1%	-10,1%	
		Dynamically controlled AV dedicated lane	-	-5,6%	-5,6%	-5,6%	-14,0%	-18,5%	-18,5%	-18,5%	
	Parking price regulation	Baseline	0,0%	12,9%	9,0%	-1,0%	-10,1%	-19,7%	-19,7%	-19,7%	
		Park inside	-	5,0%	8,4%	9,2%	12,5%	12,9%	12,9%	12,9%	
		Return to origin	-	12,6%	10,8%	16,5%	17,0%	22,8%	22,8%	22,8%	
		Drive around	-	7,0%	14,6%	20,8%	22,7%	20,8%	20,8%	20,8%	
		Park outside	-	7,5%	1,1%	1,1%	-4,1%	-2,5%	-2,5%	-2,5%	
	Replacing on-street parking	Baseline	0,0%	-8,6%	0,5%	8,4%	16,4%	12,8%	12,8%	12,8%	
		Space for public use	-	0,6%	-5,0%	-1,5%	-2,8%	-0,7%	-0,7%	-0,7%	
		Driving lanes	-	12,7%	12,8%	13,8%	18,4%	13,8%	13,8%	13,8%	
		Pick-up/drop-off	-	0,3%	-0,3%	6,2%	3,8%	10,7%	10,7%	10,7%	
	Automated ride sharing	Baseline	0,0%	14,5%	12,3%	12,4%	9,5%	8,5%	8,5%	8,5%	
		Automated ridesharing	-	4,3%	4,2%	-9,6%	-15,7%	-20,1%	-20,1%	-20,1%	
	Green Light Optimised Speed Advisory	Baseline	0,0%	14,5%	12,3%	12,4%	9,5%	8,5%	8,5%	8,5%	
		GLOSA	-	-3,2%	0,4%	2,8%	2,8%	2,8%	2,8%	2,8%	
Road safety (crashes per veh-km)	Dedicated lanes for CAVs	Baseline	0,0%	-7,9%	-12,8%	-27,4%	-47,8%	-66,2%	-77,5%	-87,1%	Micro-simulation (Manchester)
		Motorway and A road (fixed)	-	2,0%	-11,4%	-26,3%	-40,0%	-	-	-	
		A road right most lane (fixed)	-	-2,8%	-16,8%	-28,3%	-44,6%	-	-	-	
		A road left most lane (fixed)	-	-9,5%	-23,3%	-35,6%	-46,6%	-	-	-	
		Motorway only (fixed)	-	7,4%	-7,0%	-19,3%	-39,9%	-	-	-	
	Parking price regulation	Baseline	0,0%	22,0%	7,3%	-7,4%	-31,4%	-42,7%	-60,3%	-66,9%	Micro-simulation (Santander)
		Drive around without parking	-	14,8%	43,1%	-12,4%	-22,6%	-41,8%	-45,6%	-67,4%	
		Balanced scenario: park inside centre (13%), return to origin (22%), outside centre (45%), or drive around (20%)	-	21,8%	2,3%	-7,1%	-25,4%	-30,2%	-47,6%	-54,6%	
		Return to Origin (33%) or Park Outside centre (67%)	-	8,1%	7,1%	-5,3%	-23,4%	-39,1%	-49,1%	-55,8%	
	Replacing on-street parking	Baseline	0,0%	-14,1%	-25,4%	-47,0%	-59,7%	-77,0%	-84,3%	-91,6%	Micro-simulation (Leicester)
		Removing half of the on-street parking spaces	-10,1%	-16,7%	-32,5%	-50,7%	-61,9%	-79,3%	-84,5%	-92,6%	
		Replacing with driving lanes	-14,0%	-28,1%	-41,8%	-55,1%	-68,0%	-82,5%	-88,0%	-94,0%	

		Replacing with pick-up and/or drop-off points	-2,7%	-15,9%	-30,6%	-49,7%	-60,4%	-80,3%	-85,1%	-92,2%	
		Replacing with public spaces	-17,9%	-28,1%	-42,2%	-57,4%	-69,1%	-81,4%	-88,0%	-94,1%	
		Replacing with cycling lanes	-15,6%	-31,1%	-43,8%	-55,9%	-68,5%	-81,9%	-87,8%	-94,4%	
	Automated ride sharing	Baseline	0,0%	6,7%	-11,6%	-32,1%	-45,8%	-69,0%	-76,3%	-87,1%	Micro-simulation (Manchester)
		5% demand served - 20% willingness to share	-	0,7%	-3,9%	-17,3%	-27,9%	-58,5%	-71,3%	-86,5%	
		5% demand served - 50% willingness to share	-	5,2%	-7,0%	-13,7%	-30,2%	-57,5%	-70,1%	-84,7%	
		5% demand served - 80% willingness to share	-	-0,5%	-5,6%	-20,6%	-34,5%	-59,7%	-65,9%	-85,1%	
		5% demand served - 100% willingness to share	-	-3,5%	-10,4%	-24,3%	-30,3%	-58,9%	-68,6%	-84,5%	
		10% demand served - 20% willingness to share	-	9,0%	3,9%	-4,7%	-29,3%	-52,7%	-66,6%	-84,4%	
		10% demand served - 50% willingness to share	-	7,2%	-6,8%	-9,8%	-32,4%	-55,2%	-68,9%	-84,5%	
		10% demand served - 80% willingness to share	-	7,8%	-1,8%	-17,8%	-35,5%	-60,2%	-66,5%	-85,9%	
		10% demand served - 100% willingness to share	-	5,5%	-3,7%	-14,3%	-35,6%	-61,2%	-68,5%	-86,0%	
		20% demand served - 20% willingness to share	-	-6,0%	-11,3%	-10,0%	-25,2%	-50,6%	-61,3%	-80,1%	
		20% demand served - 50% willingness to share	-	-9,9%	-15,6%	-22,9%	-32,1%	-54,7%	-65,8%	-82,3%	
		20% demand served - 80% willingness to share	-	-15,2%	-17,3%	-22,7%	-43,0%	-58,3%	-66,0%	-83,6%	
		20% demand served - 100% willingness to share	-	2,6%	-7,1%	-22,6%	-41,5%	-60,3%	-70,2%	-86,8%	
	Green Light Optimised Speed Advisory	Baseline	0,0%	25,7%	17,1%	24,9%	8,1%	-48,3%	-55,7%	-84,5%	Micro-simulation (Manchester)
		GLOSA on 1 Intersection	0,0%	21,1%	13,5%	25,3%	21,7%	-44,6%	-49,8%	-82,7%	
		GLOSA on 2 Intersections	0,0%	5,9%	6,4%	12,7%	7,8%	-46,9%	-56,5%	-87,1%	
		GLOSA on 3 Intersections	0,0%	15,0%	6,2%	9,6%	12,1%	-46,6%	-56,7%	-86,9%	
Parking space requirement	Road use pricing	Baseline	0,0%	-6,1%	-9,6%	-18,9%	-24,6%	-31,2%	-31,2%	-31,2%	Delphi (expert survey)
		Empty km pricing	-	-1,6%	-5,4%	-5,8%	-10,5%	-10,5%	-10,5%	-10,5%	
		Static toll	-	4,6%	6,3%	3,0%	1,8%	1,7%	1,7%	1,7%	
		Dynamic toll	-	-4,3%	-2,5%	-3,8%	-0,3%	-0,3%	-0,3%	-0,3%	
	Dedicated lanes for AVs	Baseline	0,0%	-3,8%	-3,7%	-8,9%	-14,6%	-25,2%	-25,2%	-25,2%	
		Outermost motorway lane	-	-0,4%	-3,8%	-3,9%	-3,8%	-3,1%	-3,1%	-3,1%	
		Innermost motorway lane	-	0,3%	-3,7%	-3,7%	-14,1%	-10,7%	-10,7%	-10,7%	
		Outermost motorway lane and A-road	-	0,3%	-3,7%	-3,7%	-10,1%	-10,6%	-10,6%	-10,6%	
		Dynamically controlled AV dedicated lane	-	-0,4%	-3,8%	-3,9%	-3,8%	-4,3%	-4,3%	-4,3%	
	Parking price regulation	Baseline	0,0%	-3,7%	-13,0%	-17,2%	-15,3%	-29,9%	-29,9%	-29,9%	
		Park inside	-	-0,1%	-7,0%	-16,1%	-28,8%	-36,3%	-36,3%	-36,3%	
		Return to origin	-	-1,9%	-1,8%	-5,0%	-10,7%	-18,7%	-18,7%	-18,7%	
		Drive around	-	-3,7%	-1,8%	-13,4%	-23,0%	-34,3%	-34,3%	-34,3%	
		Park outside	-	-1,9%	-5,7%	-4,2%	-12,6%	-11,7%	-11,7%	-11,7%	
	Replacing on-street parking	Baseline	0,0%	10,2%	6,7%	7,8%	8,4%	-2,6%	-2,6%	-2,6%	
		Space for public use	-	-27,6%	-27,6%	-22,6%	-26,6%	-29,6%	-29,6%	-29,6%	
		Driving lanes	-	-9,6%	-9,5%	-10,1%	-12,5%	-19,6%	-19,6%	-19,6%	
		Pick-up/drop-off	-	-17,2%	-27,1%	-29,6%	-38,2%	-44,2%	-44,2%	-44,2%	
	Automated ride sharing	Baseline	0,0%	0,7%	4,5%	-11,1%	-17,2%	-31,7%	-31,7%	-31,7%	
		Automated ridesharing	-	0,3%	-3,3%	-12,2%	-9,9%	-23,0%	-23,0%	-23,0%	
	Green Light Optimised Speed Advisory	Baseline	0,0%	0,7%	4,5%	-11,1%	-17,2%	-31,7%	-31,7%	-31,7%	
		GLOSA	-	-2,7%	-2,7%	-2,7%	-2,7%	-2,7%	-2,7%	-2,7%	
	Baseline	no policy intervention	0,0%	2,7%	8,0%	19,7%	34,7%	47,3%	-	-	

Parking space demand	Road use pricing	Static toll: 10 euros	-34,2%	-32,9%	-31,6%	-30,8%	-30,1%	-28,0%	-	-	System dynamics
	Parking price regulation	Adjusted parking behaviour (Balanced scenario)	-28,1%	-28,7%	-28,2%	-28,1%	-26,6%	-27,1%	-	-	
	Replacing on-street parking	Removing half of spaces	-22,2%	-17,3%	-8,0%	14,9%	34,2%	47,3%	-	-	
		Replacing with driving lanes	-20,5%	-15,6%	-2,0%	25,3%	44,8%	57,3%	-	-	
	Automated ride sharing	20% of demand & 100% willing to share	0,0%	2,7%	7,8%	19,3%	34,4%	46,8%	-	-	
Public health	Road use pricing	Baseline	0,0%	2,1%	3,8%	7,4%	7,4%	11,8%	11,8%	11,8%	Delphi (expert survey)
		Empty km pricing	-	7,7%	7,7%	5,7%	9,6%	9,6%	9,6%	9,6%	
		Static toll	-	10,8%	14,3%	10,8%	9,0%	9,0%	9,0%	9,0%	
		Dynamic toll	-	11,1%	11,1%	9,0%	5,4%	7,1%	7,1%	7,1%	
	Dedicated lanes for AVs	Baseline	0,0%	-5,7%	-5,7%	-5,8%	-6,2%	-11,2%	-11,2%	-11,2%	
		Outermost motorway lane	-	-3,8%	-5,5%	-0,4%	3,2%	8,7%	8,7%	8,7%	
		Innermost motorway lane	-	-0,4%	-0,2%	-0,4%	-3,8%	3,5%	3,5%	3,5%	
		Outermost motorway lane and A-road	-	-0,4%	-5,6%	3,1%	-4,3%	3,1%	3,1%	3,1%	
		Dynamically controlled AV dedicated lane	-	-0,4%	-3,8%	3,0%	3,1%	4,8%	4,8%	4,8%	
	Parking price regulation	Baseline	0,0%	3,6%	1,8%	5,5%	5,6%	8,0%	8,0%	8,0%	
		Park inside	-	-0,1%	1,8%	3,7%	5,6%	8,0%	8,0%	8,0%	
		Return to origin	-	-3,8%	0,0%	0,5%	-1,3%	-1,9%	-1,9%	-1,9%	
		Drive around	-	-3,8%	-13,5%	-17,7%	-23,8%	-23,8%	-23,8%	-23,8%	
		Park outside	-	-0,1%	-0,1%	1,8%	3,7%	7,9%	7,9%	7,9%	
	Replacing on-street parking	Baseline	0,0%	0,3%	2,3%	6,8%	9,8%	10,3%	10,3%	10,3%	
		Space for public use	-	10,7%	18,8%	23,9%	33,5%	44,5%	44,5%	44,5%	
		Driving lanes	-	-3,7%	-8,2%	-20,1%	-16,1%	-32,1%	-32,1%	-32,1%	
		Pick-up/drop-off	-	2,2%	2,2%	8,3%	10,4%	12,9%	12,9%	12,9%	
	Automated ride sharing	Baseline	0,0%	2,5%	4,5%	7,0%	7,0%	7,0%	7,0%	7,0%	
		Automated ridesharing	-	4,4%	4,9%	8,8%	8,8%	8,8%	8,8%	8,8%	
	Green Light Optimised Speed Advisory	Baseline	0,0%	2,5%	4,5%	7,0%	7,0%	7,0%	7,0%	7,0%	
		GLOSA	-	0,2%	0,2%	0,2%	0,2%	0,2%	0,2%	0,2%	
Equal accessibility of transport	Road use pricing	Baseline	0,0%	-0,7%	5,4%	8,5%	13,1%	14,6%	14,6%	14,6%	Delphi (expert survey)
		Empty km pricing	-	-3,8%	-3,8%	-3,7%	-1,1%	-2,6%	-2,6%	-2,6%	
		Static toll	-	-8,2%	-5,2%	-4,0%	-1,0%	2,0%	2,0%	2,0%	
		Dynamic toll	-	-5,7%	-5,7%	-5,7%	-4,2%	-5,7%	-5,7%	-5,7%	
	Dedicated lanes for AVs	Baseline	0,0%	4,2%	4,2%	4,2%	6,3%	6,3%	6,3%	6,3%	
		Outermost motorway lane	-	-3,2%	-4,9%	0,2%	-8,4%	-5,0%	-5,0%	-5,0%	
		Innermost motorway lane	-	0,2%	0,2%	0,1%	-3,2%	0,3%	0,3%	0,3%	
		Outermost motorway lane and A-road	-	3,6%	0,2%	8,8%	0,3%	5,5%	5,5%	5,5%	
		Dynamically controlled AV dedicated lane	-	0,2%	-3,2%	5,4%	0,3%	3,7%	3,7%	3,7%	
	Parking price regulation	Baseline	0,0%	3,9%	5,8%	11,5%	16,3%	24,8%	24,8%	24,8%	
		Park inside	-	7,6%	5,9%	5,9%	3,6%	1,2%	1,2%	1,2%	
		Return to origin	-	3,8%	9,6%	13,3%	21,5%	22,4%	22,4%	22,4%	
		Drive around	-	0,2%	-2,1%	-3,8%	-3,8%	-8,0%	-8,0%	-8,0%	
		Park outside	-	-3,5%	-5,3%	0,3%	-0,1%	1,8%	1,8%	1,8%	

	Replacing on-street parking	Baseline	0,0%	-1,3%	-0,8%	0,7%	7,7%	12,7%	12,7%	12,7%	
		Space for public use	-	-3,7%	-9,7%	-12,1%	-10,1%	-13,1%	-13,1%	-13,1%	
		Driving lanes	-	0,3%	4,8%	10,8%	10,9%	20,9%	20,9%	20,9%	
		Pick-up/drop-off	-	-1,7%	0,3%	6,8%	9,3%	9,8%	9,8%	9,8%	
	Automated ride sharing	Baseline	0,0%	9,1%	9,1%	12,9%	18,7%	17,1%	17,1%	17,1%	
		Automated ridesharing	-	9,1%	13,7%	18,6%	17,1%	13,8%	13,8%	13,8%	
	Green Light Optimised Speed Advisory	Baseline	0,0%	9,1%	9,1%	12,9%	18,7%	17,1%	17,1%	17,1%	
		GLOSA	-	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	
Average commuting distances	Baseline	no policy intervention	0,0%	0,0%	0,0%	0,0%	0,0%	1,0%	-	-	System dynamics
	Road use pricing	Static toll: 10 euros	0,0%	0,0%	0,0%	0,0%	0,0%	1,0%	-	-	
	Parking price regulation	Adjusted parking behaviour (Balanced scenario)	0,0%	0,0%	0,0%	0,0%	0,0%	1,0%	-	-	
	Replacing on-street parking	Removing half of spaces	0,0%	0,0%	0,0%	0,0%	0,0%	1,0%	-	-	
		Replacing with driving lanes	0,0%	0,0%	0,0%	0,0%	0,0%	1,0%	-	-	
	Automated ride sharing	20% of demand & 100% willing to share	0,1%	0,1%	0,2%	0,3%	0,5%	1,0%	-	-	