D7.4 Long-term impacts of cooperative, connected, and automated mobility on freight transport

Deliverable D7.4 – WP7 – PU

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Work package 7, Deliverable D7.4

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Executive summary

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

This report specifically focuses on freight transport, providing an analysis for the long-term impacts of different freight transport sub-use cases. The impacts to be studied have been defined in the Deliverable 3.1, which provided a preliminary taxonomy of the potential impacts of CCAM. The long-term impacts presented in this report are those described as wider impacts, which are road safety, CO_2 emissions, parking space, energy efficiency and public health.

After an extensive literature review and a stakeholder reference group (SRG) workshop, a preliminary list of the urban transport sub-use cases was developed, presented in Deliverable 7.1. The proposed automated freight transport sub-use cases have been prioritized for their consideration in further investigation. During prioritization, factors such as widespread studies being followed on those sub-use cases and the feasibility of impact assessment have been considered. The sub-use cases that are presented in this report are on automated urban delivery, automated consolidation, and hub-to-hub automated transport.

For assessing the road safety impacts, qualitative and quantitative analysis have been used. Latter is based on microscopic simulation and the Surrogate Safety Assessment Model for identifying potential crash-causing conflicts. Emissions of freight vehicles are based on the mileage and type of the fleet. Finally, parking space, energy efficiency and public health were conducted from the Delphi panel.

The key result obtained in this deliverable is that automated, consolidated freight transport significantly improves road safety when the AV penetration rate reaches 100%, especially when they are performed during off-peak hours and night.

1 Introduction

1.1 LEVITATE

Societal **Lev**el **I**mpacts of Connec**t**ed and **A**utoma**t**ed Vehicl**e**s (LEVITATE) is a European Commission supported Horizon 2020 project with the primary 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 the technologies to achieve societal objectives.

Specifically LEVITATE has four key objectives:

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

1.2 Work package 7 and Deliverable 7.4 within LEVITATE

WP7 focuses on the impacts that the deployment of cooperative, connected and autonomous vehicles, particularly automated vans and trucks, are expected to have on logistics and freight transport. Forecasting of impacts will consider these components: (i) Automation in parcel delivery, (ii) Automation in consolidation and (iii) hub-to-hub automated transport.

Forecasting will be 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 freight transport. More specifically, the objectives of WP7 are:

- To identify how each area of impact (safety, mobility, environment, economy, and society) will be affected by CCAM in freight transport, with focus on the transition towards higher levels of automation.
- To test interactions of the examined impacts in freight transport scenarios; and,

- To create a policy support tool (PST) to help authorities to make the right decisions on policy measures concerning the introduction of CCAM.

This report (Deliverable 7.4) presents the long-term impacts of CCAM on freight transport and is based on impacts as identified and defined in WP3 and WP4 (Elvik et al., 2019, Zach et al., 2019). The specific nature of long-term context has been defined in D7.1 (Hu et al., 2019). The main methodological approaches to forecast the long-term impacts are microscopic simulation (micro-simulation), operations research, and Delphi. Microsimulation will estimate the road network-level impacts of the integration of different impacts for different transport types, modes and actors, which is used to assess road safety and traffic flow. Results from operations research from D7.2 (Hu et al., 2021) provides the km travelled, which is used to complement the results of micro-simulation, and to calculate the emissions. The wider impacts of parking space, energy efficiency, and public health is estimated via Delphi.

Table 1.1 shows an overview of the full list of impacts considered in the PST for WP7, along with a short description and the unit of measurement. Highlighted are those that are handled in this deliverable.

Table 1.1: Overview of the impacts in WP7. Highlighted are the long-term impacts for this deliverable.

Impact	Description / measurement	Unit of Measurement
Short term impacts / direct impacts		
Travel time	*Average duration of a 5Km trip inside the city centre*	*min*
Vehicle operating cost	*Direct outlays for operating a vehicle per kilometre of travel*	*€/km*
Freight transport cost	*Direct outlays for transporting a tonne of goods per kilometre of travel*	*€/tonne-km*
Medium term impacts / systemic impacts		
Congestion	*Average delays to traffic (seconds per vehicle-kilometer) as a result of high traffic volume*	*s/veh-km*
Long term impacts / wider impacts		
Road safety	*Number of potential crashes per vehicle-kilometer driven (temp. until crash relation is defined).*	*crashes/ veh-km*
Parking space	*Required parking space in the city centre per person*	*m^2/person*
Energy efficiency	*Average rate (over the vehicle fleet) at which propulsion energy is converted to movement*	%
CO_2 due to vehicles	*Concentration of CO_2 pollutants as grams per vehicle-kilometer (due to road transport only)*	*t/day*
Public health	*Subjective rating of public health state, related to transport (10 points Likert scale)*	-

2 Sub-use cases

A stakeholder reference group workshop (presented in detail in D7.1 by Hu et al., 2019) involving city administrators and representatives from industry was held to gather views on the future of CCAM and possible sub-use cases (SUC) of freight transport. A list of SUCs of interest for freight transport from the perspective of CCAM was developed. Within LEVITATE, this list was prioritized and refined within subsequent tasks in the project to inform the interventions and scenarios related to freight transport. In turn, these SUCs will be included in the LEVITATE Policy Support Tool (PST).

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

- Scientific literature: Indicating the scientific knowledge and the available assessment methodologies for the sub-use cases. However, this might not be directly linked to their importance / relevance for practice.
- Roadmaps: Indicating the relevance of sub-use cases from the industrial/ political point of view, independent of available scientific methodologies.
- SRG Workshop: Containing first-hand feedback for the sub-use cases but might only reflect the opinions of organisations and people who participated.

The automated freight transport related sub-use cases that are:

- **Automated urban delivery**: Future parcel delivery by automated vans and delivery robots.
- **Automated consolidation**: Extension of automated urban delivery by applying consolidation at city-hubs.
- **Hub-to-hub automated transport**: Effects of transfer hubs to facilitate automated trucks.
- **Platooning on urban highway bridges**: Impacts of increasing the density of heavy freight transport on bridge infrastructure (which are described in D7.3)

2.1 Automated urban delivery

The automated urban delivery sub-use case compares the performance of parcel delivery in urban areas via manual delivery personnel and (semi-)automated concepts. While the automated road-based (delivery) vehicles are well-studied, the operation of delivery robots or micro-vehicles is still an under-researched topic (Baum et al. 2019). Studies show that using smaller, electrified vehicles and robots addresses several acute problems: emissions, navigation in confined inner-city areas and the limitation of working time for manual parcel delivery (Jennings et al., 2019, Figliozzi et al., 2020). There are concepts where the autonomous delivery robots are airborne drones (Dorling et al. 2017), but the operation of drones especially in crowded urban environment is controversial and legally challenging. Therefore, this not further considered in the project.

Based on the current manual delivery process, the envisioned automation technologies and concepts that will emerge in the next decades, we consider these delivery scenarios:

- **Manual delivery** (status quo) is used as a base scenario for comparison.

- **Semi-automated delivery** assumes that the delivery process is not fully automated yet. While the delivery van is automated, personnel are still undertaking the delivery task. However, since they do not need to switch between delivery and driving tasks, time can be saved during each stop.
- **Automated delivery** is where so-called robo-vans and small autonomous delivery robots replace all service personnel and operate beyond the road (to the off-loading areas using pavement, pedestrian area, etc.). The automated van functions as a mobile hub where they perform short delivery trips to end-customers, i.e., a hub-and-spoke setup with moving hubs. This human-less delivery process can be carried out during off-peak hours when road traffic volumes are lower and be extended to evening or nighttime delivery. For this concept, we assume that the parcel capacity of the van will be significantly reduced. The main reason is that it has to carry the delivery robots and the necessary equipment to load them.
- **Automated night delivery** is the same as above, but deliveries are limited to night time delivery only. Since the delivery time is restricted to night time only, this scenario will increase in the fleet size since the same volume of deliveries will have to be made in significantly less time compared to the previous scenario.

The delivery performance and the limiting factors are shown in Table 2.1.

Table 2.1: Performance of the delivery scenarios and their main limiting factors (red).

Delivery scenarios	**Sub-use case specific scenarios (Automated urban delivery)**				
	Delivery scenario parameters				
	Delivery shifts	Avg. parcels per shift	Avg. parcels per stop	Service time per stop	Delivery vehicle
Manual delivery	6:30 – 15:00	150	Variable	5	Van
Semi-automated delivery	6:30 – 15:00	180	Variable	4	Automated van
Automated delivery	9:00 – 15:00, 18:00 – 24:00, 0:00 – 6:00	100	Variable	10	Robo-Van
Automated night delivery	18:00 – 24:00, 0:00 – 6:00	100	Variable	10	Robo-Van

2.2 Automated freight consolidation

The automated consolidation sub use case is a continuation of automated urban delivery. In this setting, the parcel delivery companies will consolidate their parcels at city-hubs instead of operating independently and delivering parcels straight to their final recipients. Ideally, the city-hubs and the last-mile delivery operate on a white-label basis, i.e., the delivery vehicles are not bound to a specific delivery company but operate the service for all companies. This removes a lot of redundancy in the delivery system nowadays. In addition, since these city-hubs are closer to the city center than the original distribution centers, final delivery routes in a consolidated scenario are significantly shorter. This has a positive impact on the traffic and the environment (Allen et al. 2012, Quak et al. 2016). While the scientific works are more focused on finding the optimal locations for the hubs (Charisis et al. 2020), it is more of a political and urban planning problem in the real world.

We compare the following delivery scenarios:

- **Manual delivery** refers to the same scenario as in the previous SUC
- **Automated delivery** refers to the automated delivery scenario as in the previous SUC
- **Manual delivery with bundling at city-hubs** uses bundled parcel delivery via city-hubs, but both the servicing of city-hubs and the delivery to end-customers are done manually.
- **Automated delivery with bundling at city-hubs** is the final scenario that combines the automated delivery via robo-vans and the city-hubs for bundling.

In all automated scenarios, we assume that the delivery is done during day and night (c.f. automated urban delivery SUC), whereas the transport from distribution centers to city-hubs is done during the night via automated trucks. Solutions or prototypes for automatic loading and unloading already exist for packages and pallets (Cramer et al. 2020).

2.3 Hub-to-hub automated transport

This sub-use case studies the impacts of AV truck terminals functioning as transfer hubs. The goal of these hubs is to facilitate the transition towards level 5 automation by supporting the operation of level 4 automated trucks that can operate on highways but not in urban environment. It is assumed that outbound freight containers from the city are passed to AV trucks at the terminal, which then take over the long-haul highway segment. At an AV truck terminal of the destination city, the container is passed to a manually operated truck again to bring it to the destination. An ideal location for such a terminal is at the city border with direct or good access to the highway. Figure 2.1 shows how this concept should work.

The main benefit of this approach enabled by AV truck terminal is that

- Long-haul freight transport is the most unappealing part for truck drivers, but the first thing that can be automated. Besides social benefits, the cost reduction is a significant factor. This concept supports the usage of AV trucks.
- For the urban highway, it is possible to reduce the usage during daytime and shift the freight transport towards night. This can be achieved by coordinating AV trucks to only depart during night hours.

A study by Berger (2016) shows that this concept is highly attractive for the long haul, where the driver wage takes one third of the total transport costs. It is also expected that the hub-to-hub connections will be dominated by autonomous trucks, while hub-to-delivery will be executed by hybrid and full-electric small to medium sized trucks (Novak, 2016).

For this SUC we consider a small area around a potential AV truck terminal including an urban highway segment with ramps. Two scenarios are compared:

- **Status quo** where manual container trucks are operating between their origin and destinations directly across the day.
- **Operation via transfer terminal:** During the day, manual trucks deliver their freight from origin to the AV truck terminal. During night, AV trucks ship the containers from the terminal to the destination terminals. Similarly, AV trucks from other terminals arrive across day and night, while the further transport into the city via manual trucks happen during the day.

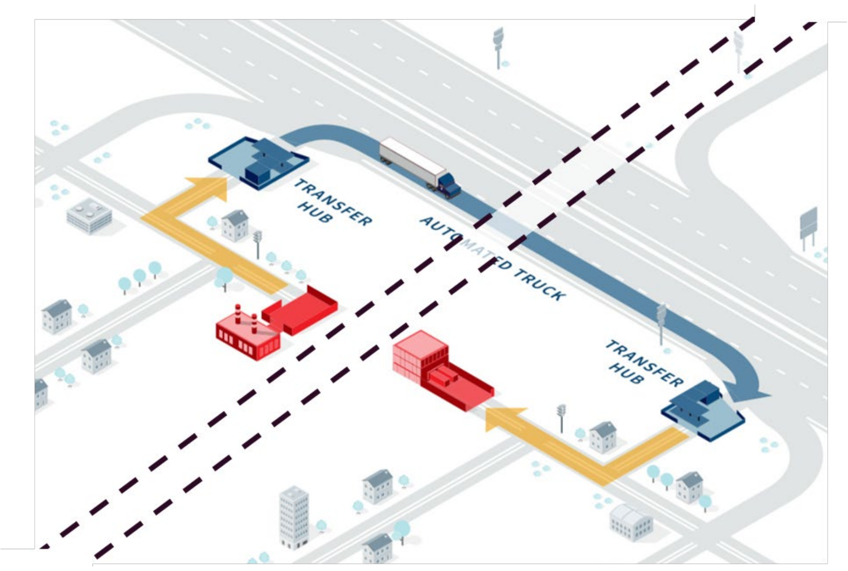


Figure 2.1: Function of the automated transfer hub. Human-operated trucks deliver the containers to the transfer hub (yellow arrow) and from there automated trucks carry them on to the highway (blue arrow).

3 Methods

In WP3 the types of impacts were estimated and forecast using appropriate assessment methods, such as micro-simulation, operations research and Delphi panel (Elvik et al., 2019).
All these results relating to the relationships between sub-use cases, impacts and any intermediate parameters serve as input to WP8, specifically the Policy Support Tool (PST) that is being developed. The results will be integrated within the PST modules and functionalities so that impact assessment can be carried out by the users.

3.1 Hybrid assessment approach

For automated delivery and automated consolidation SUCs, a hybrid assessment method based on micro-simulation and operations research was applied. We use micro-simulation to capture the traffic impacts of a typical delivery tour of one delivery vehicle. These impacts are then scaled up using operations research, where we compute the delivery tours, see Figure 3.1.

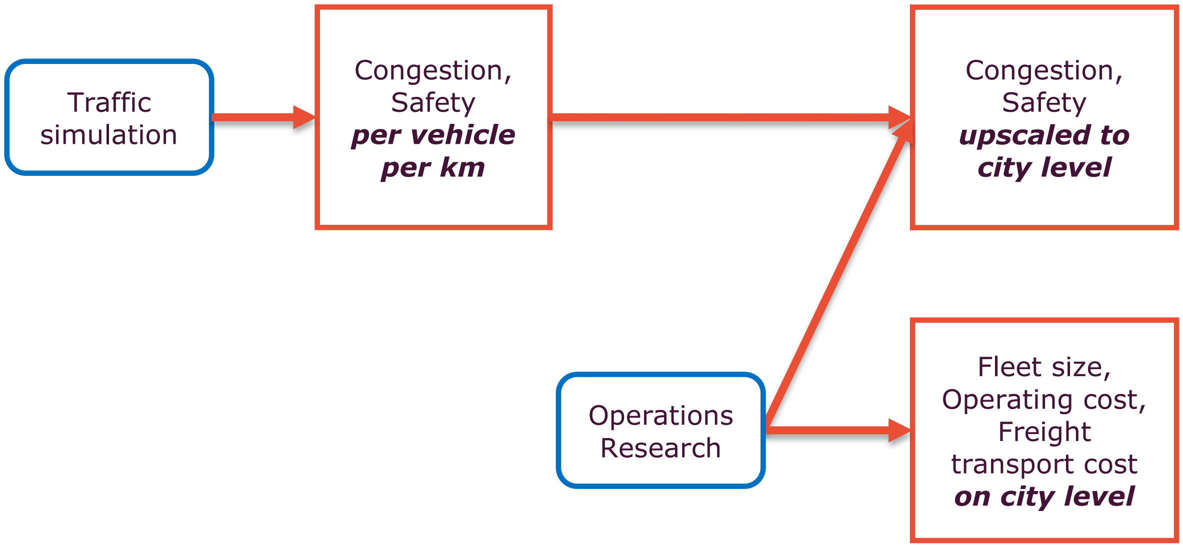


Figure 3.1: Flowchart for the hybrid assessment approach.

3.2 Operations research

Within the hybrid assessment approach, operations research (OR) methods are applied as they are described in D7.2 (Hu et al., 2021). OR is widely used in freight transport (Lagorio et al., 2016) and calculates results for freight transport costs, fleet operation costs, and vehicle mileage. They mainly consist of optimisation algorithms for route planning, also commonly known as the vehicle routing problem (VRP), where the goal is to calculate the optimal route or set of routes at the lowest possible cost (and often also the shortest possible time) from a given depot to a number of customers (Toth and Vigo, 2014).

The underlying algorithm for calculating the delivery scenarios is based on optimising the routing of the delivery vehicles. In all delivery variants considered, the delivery points are assigned to a depot from which the parcels are delivered. Depending on the delivery scenario, this depot can be a logistics center or a city-hub (in case of consolidated delivery). Subsequently, a problem instance of the Capacitated Vehicle Routing Problem (CVRP) (Toth and Vigo, 2014) is generated for each depot, with the delivery addresses acting as so-called customers, see example in Figure 3.3. Finally, these instances are solved using the Savings algorithm (Clarke and Wright, 1964). This algorithm is able to handle large size problems which is the case here when the full city is considered. Finally, the required consolidation trips between the individual depots are calculated.

If the demand for parcels at a delivery address exceeds the capacity of a single delivery vehicle, we divide it into multiple virtual delivery addresses at the same location, with each of these having a maximum demand for parcels equal to the capacity of the delivery vehicle. When all delivery tours are calculated, the number of routes and the sum of their lengths are used as input for the corresponding (cost and distance) impact indicators.

In this deliverable, these outputs are used to upscale the micro-simulation results to city-level. For a detailed description for the operations research methods, we refer to D7.2.

3.3 Microscopic simulation

Micro-simulation methods and the study network models have been described in D7.3 (Hu et al., 2021). It is used within the AIMSUN next framework to assess the traffic impacts such as congestion and road safety.

For the automated delivery and automated consolidation SUCs, the simulation area is based on Vienna, an OSM import from the 19th district. For the calibration, we added traffic volume and traffic lights which mimic the real traffic conditions. The delivery tours are approx. 3km long and we use two settings: One route mimics the periphery area by using low-traffic roads, and another route mimics the urban area by using more crowded roads. Then the delivery scenarios with different settings are simulated: manual vs. automated delivery vehicle, urban vs. rural, and daytime vs. nighttime.

In addition, simulations with different AV penetration rates are performed for each scenario. In the background traffic, three types of vehicles are used:

- Manual vehicles: These are the status-quo road users in AIMSUN with default parameters.
- 1st Generation AVs: limited sensing and cognitive ability, long gaps, earlier anticipation of lane changes than human-driven vehicles and longer time in give way situations.
- 2nd Generation AVs: advanced sensing and cognitive ability, data fusion usage, confidence in taking decisions, small gaps, early anticipation of lane changes than human-driven vehicles and less time in give way situations.

Finally, the results of the micro-simulation are upscaled to city-level via the hybrid assessment approach, i.e., combining the results for different areas in Vienna according to their level of urbaness, and use the freight mileage in these areas as a multiplier to upscale the micro-simulation results. For a detailed description on micro-simulation, we refer to D7.3.

3.4 Delphi

The Delphi method was introduced in D7.2 (Hu et al., 2021). It is based on a repetitive interview process in which the respondent can review his or her initial answers and thus change the overall information on each topic (Hsu & Sandford, 2007). In this deliverable, the Delphi method is used to assess the wider impacts that are difficult to quantify, namely parking space, energy efficiency by CCAM, and public health. Initially, a long list of experts was identified for each use case (i.e., urban transport, passenger cars and freight transport), and contacted via an introductory e-mail asking them to express a willingness to participate. Those who responded positively participated in the main Delphi process, amounting to 70 experts in total (5 experts accepted to answer to 2 questionnaires).

The questionnaires consisted of two rounds of e-mails. During the first round, experts received a questionnaire (30-45min duration) regarding a few (2-4) policy interventions related to automated urban transport, automated passenger cars or automated freight transport, as per their specific expertise. Before starting the questionnaire, they were asked to reply to the consent form accepting the use of the information they provided in the questionnaire. They were then asked to evaluate the potential influence of the proposed interventions on different impact areas. Their answers were then analysed in order to create (anonymous) summary data for the different CCAM related interventions. These results were distributed with the second-round questionnaire and gave respondents the opportunity to reflect on the first-round outcomes before providing their answers again. In some cases it led to respondents changing their first round responses to something conforming more to the answers provided by other respondents. For a detailed description on Delphi, we refer to D7.2.

4 Long-term Impacts

In this deliverable, we discuss the long-term impacts of CCAM on freight transport. These are road safety, parking space, energy efficiency, emissions, and public health. Road safety has a qualitative part, describing the upcoming challenges and behavioural changes, and a quantitative part on the basis of the micro-simulations. Emissions are assessed by operation research methods where the (changed) mileage of the freight vehicles are used as primary modifiers. The wider impacts on parking space, energy efficiency, emissions, and public health are based on the Delphi panel.

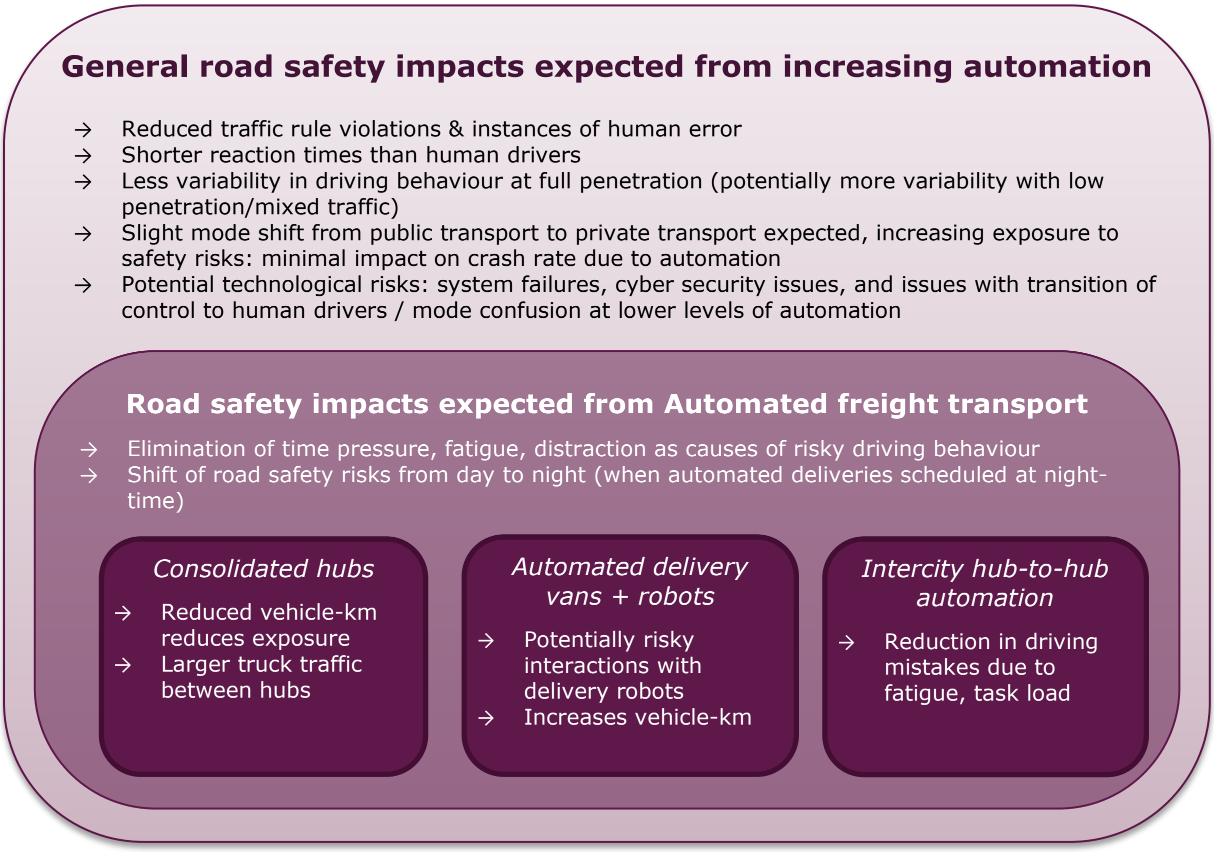
4.1 Road Safety related impacts

Within LEVITATE, road safety impacts of both a general increasing penetration level of CAVs in the vehicle fleet as well as the more specific interventions studied in the SUCs are evaluated using multiple approaches. First, literature is used to establish where and how increasing automation is expected to have a direct/indirect effect on road safety. These results are summarized in Section 4.1.1. Second, the effects are quantified in Section 4.1.2 using micro-simulation in AIMSUN combined with the Surrogate Safety Assessment Model (SSAM) tool which identifies potentially dangerous traffic interactions (traffic ‘conflicts’). A prediction for the resulting change in crashes is made for both baseline scenarios (increasing penetration of CAVs without automated freight transport) as well as the automated freight transport scenarios discussed in this Work Package. Third, the effects of a change in the total kilometers driven as presented in D7.2 (Hu et al., 2021).

4.1.1 Expected road safety impacts

Road safety is expected to be impacted by both a general increase in CAV penetration levels (baseline scenario) as well as specific developments related to automated freight transport. These safety impacts are summarized in Figure 4.1.

The general introduction and increasing penetration levels of Connected and Automated Vehicles (CAVs) is expected to impact road safety in several direct and indirect ways. CAVs are expected to have a lower risk of being involved in a crash than human drivers, as they are expected to obey traffic rules, to not make mistakes that human drivers make, to have lower reaction times and to exhibit less variability in driving behaviour. On the other hand, some new potential risks might be introduced by automated vehicles, such as system failures, cyber security issues, and issues related to transition of control or mode confusion. In addition, some rebound/indirect effects can be expected, caused by changes in broader factors that in turn affect road safety. Examples of these indirect impacts include changes in road safety due to changes in total distance travelled, modal split, route choice and changes in the behaviour of other road users. For a more detailed discussion of the road safety impacts of increasing automation, see Weijermars et al (2021).



General road safety impacts expected from increasing automation

- → Reduced traffic rule violations & instances of human error
- → Shorter reaction times than human drivers
- → Less variability in driving behaviour at full penetration (potentially more variability with low penetration/mixed traffic)
- → Slight mode shift from public transport to private transport expected, increasing exposure to safety risks: minimal impact on crash rate due to automation
- → Potential technological risks: system failures, cyber security issues, and issues with transition of control to human drivers / mode confusion at lower levels of automation

Road safety impacts expected from Automated freight transport

- → Elimination of time pressure, fatigue, distraction as causes of risky driving behaviour
- → Shift of road safety risks from day to night (when automated deliveries scheduled at night-time)

Consolidated hubs

- → Reduced vehicle-km reduces exposure
- → Larger truck traffic between hubs

Automated delivery vans + robots

- → Potentially risky interactions with delivery robots
- → Increases vehicle-km

Intercity hub-to-hub automation

- → Reduction in driving mistakes due to fatigue, task load

Figure 4.1 Road safety impacts of increasing automation

Regarding the more specific cases of automated delivery vans, consolidated logistic hubs and automated freight trucks several additional changes are expected to impact road safety. These include a change in driving behaviour, interactions with the delivery robots replacing human couriers and a change in modal split of freight transport, as described in the following paragraphs. In addition to these impacts, in the specific case that there is no driver in the automated van, exposure slightly decreases as there is no longer a driver that is at risk of getting (fatally) injured in a crash.

Change in distance travelled

An increase or decrease in the total distance travelled by all vehicles in the network affects the total exposure to risk and can subsequently, all else being equal, lead to an increase or decrease in crashes. Depending on the scenario implemented, different (opposing) effects on vehicle kilometers are expected. Automated delivery vans are expected to have a lower capacity than human-driven delivery vans due to the cargo space used for the delivery robots. Therefore, it is likely that more vans/trips will be needed to complete the same number of deliveries, thus increasing total distance travelled. Meanwhile, consolidation at multi-hubs throughout the city is expected to improve efficiency by using trucks rather than vans for the first leg of the trip and allowing for more efficient delivery routes, thus reducing vehicle kilometers. Thus, without consolidation, the increase in exposure could potentially lead to more crashes; however, due to safety gains in other areas such as driving behaviour, the overall road safety might not be negatively impacted. The impact of a change in total kilometers travelled is quantified using operations research for the city of Vienna.

Redirection to safer roads/different road types

In the two consolidated delivery scenarios (automated and non-automated), the lorries that are driving between the multi-hub and the city-hub will likely be using larger, safer roads on which VRUs are separated from other traffic, which is assumed in the corresponding SUCs in this document. The direct route from multi-hub to micro-hub might get busier, while other routes (on smaller streets) will experience less traffic. Even though some roads will become busier, it is likely that road safety increases because traffic will be (partially) redirected to roads that are safer by design (SWOV, 2017). The safety effects of the different road types can to a certain extent be quantified using micro-simulation, although it is questionable how well the safety level of different routes is represented in the micro-simulation model.

Driver behaviour

The replacement of traditional human-driven delivery vehicles and freight trucks with automated vehicles is expected to significantly impact driving behaviour. Human drivers of both types of vehicles can experience time pressure, fatigue, distraction, and a willingness to break traffic rules—all of which are expected to be removed in the case of (fully) automated freight vehicles. In a survey of delivery drivers in Britain by Christie & Ward (2018), drivers reported feeling the effects of time pressure, distraction, and tiredness, and indicated to sometimes break traffic rules: 47% of participants sometimes drive over the speed limit, 63% sometimes park illegally and 30% sometimes drive through a red light. Similarly, truck drivers also frequently experience time pressure (Kuiken, Overkamp, & Fokkema, 2006), and fatigue, distraction and task load are reported to be important causes of driving mistakes (SWOV, 2020). Results from a driving simulator study (Rendon-Velez et al., 2016) further confirmed this, showing that drivers adopt a more aggressive driving style when under time pressure (e.g., higher speeds, approaching intersections with higher speeds, higher acceleration, poorer lane keeping precision, driving in the left part of the lane).

We assume that automated vehicles will not experience time pressure and therefore will not exhibit the related aggressive driving behaviour. We also assume that automated vehicles will adhere to traffic rules (speed limit, stopping for a red light, etc.) and will adjust their behaviour to the current conditions. This will likely increase road safety. Unfortunately, we are not able to model these specific driver behaviours within the LEVITATE project due to limitations in the ability of micro-simulation to model imperfect human behaviour.

Time of delivery

The automation of delivery vehicles and freight trucks allows for a shift of daytime freight traffic to night-time in order to eliminate parcel deliveries during peak hours. This is therefore expected to improve road safety during the day, and increase the risk at night. This is particularly likely for the full automation (night) scenario, in which all daytime deliveries will be allocated to the night-time and the fleet size will have to increase to manage the same number of parcels within a smaller timeframe. The safety impacts of changed delivery times and the resulting changes in traffic volumes are partially estimated with micro-simulations and operations research; however, as mentioned before, we are not able to model specific driver behaviours within the LEVITATE project. A breakdown freight of mileage for different time of the day is shown in section 4.1.2.2 and Figure 4.3.

Interactions with the delivery robots

In the automated delivery scenarios (non-consolidated and consolidated), parcels are delivered by small delivery robots which generate a new set of interactions potentially impacting road safety. Unfortunately, we know very little about these interactions and their effect on road safety as, to our knowledge, no research on this has been done. Because of their small size and the fact that they will replace human couriers, it is likely that the delivery robots will mainly drive on sidewalks. This will result in busier sidewalks and interactions with VRUs and possibly other traffic (for example when crossing a road).

In an advisory report about an on-road test with delivery robots in the Netherlands, Van Petegem, Van Nes, Boele, and Eenink (2018) identified potential road safety risks related to the interaction between such robots and other road users. While some of these risks specifically apply to the on-road test, others are more broadly applicable. The latter are related to the unpredictability of the robot's behaviour, its speed in comparison to pedestrians, its low height (others might not see the robot), and the robot blocking sidewalks (especially for wheelchairs and mobility scooters). Although these risks are based on expert judgement and have yet to be researched in the field, it is important to be aware of this new set of interaction that delivery robots would introduce and how these might decrease road safety in comparison to manual delivery. Interactions with delivery robots are not accounted for within the micro-simulations and are outside the scope of the LEVITATE project. However, one might assume that these types of robots will only be widely implemented once the above-mentioned risks are mitigated.

Changes in modal split

As mentioned in the Weijermars et al (2021), changes of modal split can affect road safety. A few potential shifts in the logistics modal split are identified for this use case on automated freight transport. First, intercity hub-to-hub transport is assumed to continue using freight trucks which in time are replaced by their automized counterparts (the effects of which are described as a change in driving behaviour rather than a modal shift). In the scenario that trips from city-level distribution hubs to consumers are first consolidated at inner-city multi-hubs before switching to automated delivery vans, these consolidated trips may be conducted by larger trucks rather than delivery vans. This could result in fewer trips, but conducted by larger vehicles. In the final delivery stage, automated delivery vans with delivery robots are expected to replace human-driven delivery vans. However, it is also possible that they may replace delivery trips which now or in the future would be done by cargo bike. The extent to which these modal shifts may occur and the effects of delivery robots on road safety require additional research in order to quantify, and therefore fall outside of the scope of the LEVITATE project.

4.1.2 Quantification of traffic safety impacts

The effects on road safety of increasing automation of the vehicle fleet together with the freight scenarios are quantified using micro-simulation of motor vehicle traffic in AIMSUN combined with the SSAM which identifies potentially dangerous traffic interactions (traffic 'conflicts'). SSAM, developed by the Federal Highway Administration (FHWA), uses trajectory files from the simulation to identify instances where vehicles in the network overstep threshold values of Time to Collision (TTC) and Post Encroachment Time (PET).[1],

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[1] The default values in AIMSUN for Time to Collision (TTC=1.5 s) and Post Encroachment Time (PET=5 s) are adopted for human-driven vehicles. Due to the quicker reaction times expected for automated vehicles, 1st generation AVs allow closer interactions (TTC= 1.0s) to be regarded as safe, and 2nd generation AVs can adopt the shortest headways (TTC= 0.5s).

representing a potential crash-causing conflict. Using the theoretical probabilistic method developed by Tarko (2018), a prediction is made for the share of conflicts that result in a crash. These crash predictions are reported in the following sections for both baseline scenarios (without automated vans or transfer hubs) as well as automated urban delivery vans and transfer hubs. For the consolidation scenario of automated delivery vans, the indirect impacts of a change in delivery time and kilometers travelled is discussed.

AIMSUN, the micro-simulation software used in LEVITATE, is currently 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, including connected and automated delivery vans, is expected to decrease fatalities among VRUs by more than 90% in case of 100% penetration. The sub-use cases on freight transport are not expected to have a large additional effect specifically on vulnerable road users compared to the base scenario, and where larger potential impacts are expected (e.g., delivery robots) it is not possible to quantify the impacts with the available data and simulation methods. Therefore, impacts on VRUs are not quantified for this sub-use case.

4.1.2.1 Automated urban delivery

Using micro-simulation, we simulated the area as described in D7.3 with the two delivery routes, mimicking parcel delivery in urban area and periphery area. The results for the number of potential crashes are shown in Table 4.1 (absolute crash rate) and Figure 4.2 (percentage change relative to the initial 0% penetration rate).

As can be seen in Figure 4.2, in both the baseline scenarios as well as the automated freight scenarios, an increase in crash rates is predicted at lower penetration rates followed by a reduction in crashes when automated vehicles become increasingly in the majority. This is primarily due to interactions between human-driven vehicles and automated vehicles, which are expected to have different driving styles (e.g., AVs adopting shorter headways) and different capabilities (e.g., human drivers' longer reaction times) which may lead to an initial increase in risks when many human drivers are still on the road.

In terms of the automated urban delivery vans, the additional automation within the total vehicle fleet helps to mitigate some of the initial increase in crashes expected at low penetration rates. However, similarly to the congestion analysed in D7.3, the differences between different scenarios are marginal. The reason is that the number of delivery vehicles compared to the background traffic volume is very small.

Table 4.1: Number of potential crashes per 1000 vehicle km for the simulation scenarios.

Simulation scenario	A	B	C	D	E	F	G	H
	(100,0,0)	(80,20,0)	(60,40,0)	(40,40,20)	(20,40,40)	(0,40,60)	(0,20,80)	(0,0,100)
urban, manual van	5,5	5,8	6,2	6,3	5,5	4,4	3,5	2,8
urban, robo-van	5,3	5,0	5,9	5,5	5,8	4,5	3,2	2,7
periphery, manual van	2,6	2,9	3,0	3,1	3,0	2,1	1,6	1,3
periphery, robo-van	2,6	2,7	3,0	3,0	2,7	2,0	1,6	1,4

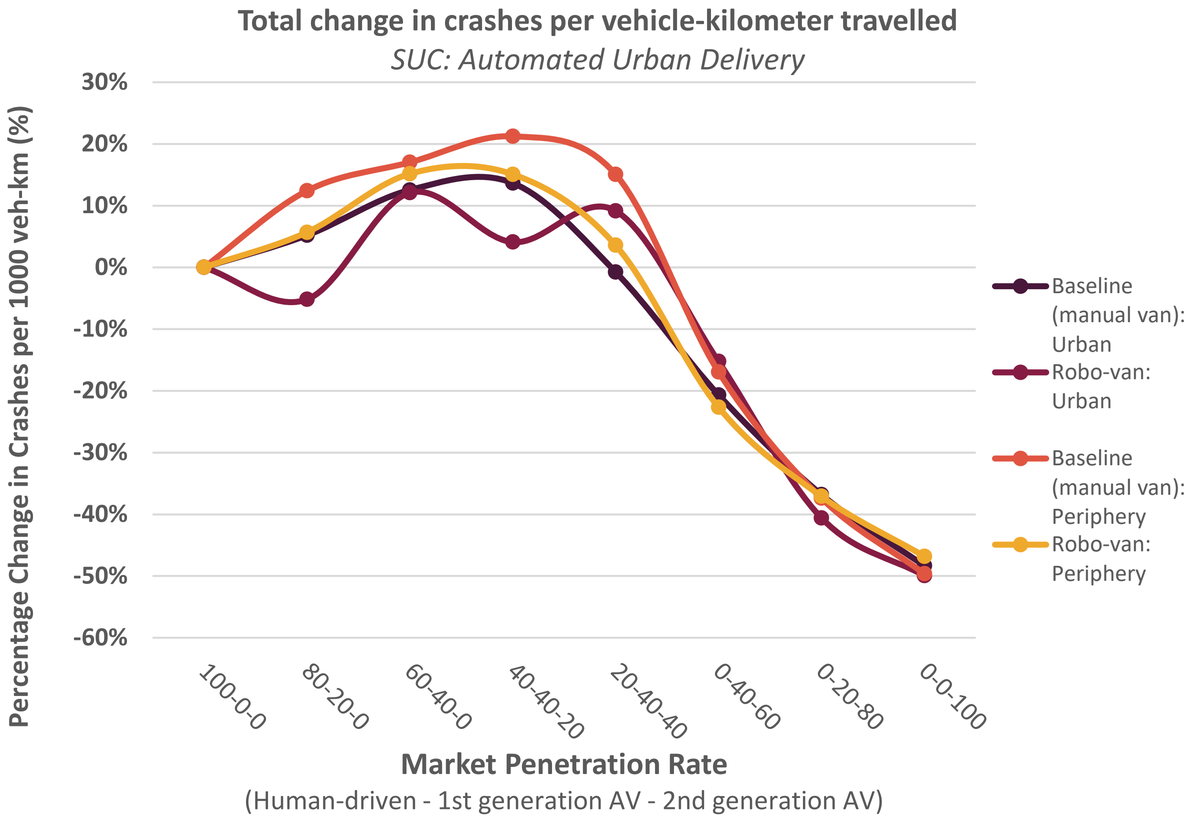


Figure 4.2: Predicted change in crashes per 1000 vehicle km for the simulation scenarios, measured in terms of percentage change from the respective starting scenario at a 0% penetration rate of automated vehicles

4.1.2.2 Automated consolidation

For the automated consolidation SUC, we assume that the number of potential crashes of the background traffic is not significantly affected by the delivery system. However, we have to take into account the different mileage of the delivery scenarios (c.f. D7.2).

For road safety, another important aspect is the time of day when the delivery tours and the consolidation tours are performed. Reasons are i) potential accidents with freight vehicles are more severe in general than with passenger cars and ii) shifting freight transport towards the nighttime greatly reduces the interactions and potential conflicts with VRUs.

We refer to Table 2.1 where we assume the delivery shifts to happen depending on the delivery scenario. For the consolidated scenarios, we assume that the delivery times are equal to manual and automated unconsolidated delivery, respectively. The consolidation tours to service the city-hubs via trucks are done at 6am for the manual scenario and between 0am and 6am in the automated scenario. The total mileage and the breakdown to the time of the day are shown in Table 4.2 and Figure 4.3.

Table 4.2: Mileage (km) for each delivery scenario and breakdown to time of the day.

	Total mileage		Time of the day							
	(Robo) Vans	Trucks	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
Manual delivery	80389		0	0	26796	26796	26796	0	0	0
Semi-automated delivery	70805		0	0	23602	23602	23602	0	0	0
Automated delivery	106177		17696	17696	0	17696	17696	0	17696	17696
Automated night delivery	106177		26544	26544	0	0	0	0	26544	26544
Manual delivery + city-hubs	24675	10445	0	0	18670	8225	8225	0	0	0
Automated delivery + city-hubs	32347	10445	10614	10614	0	5391	5391	0	5391	5391

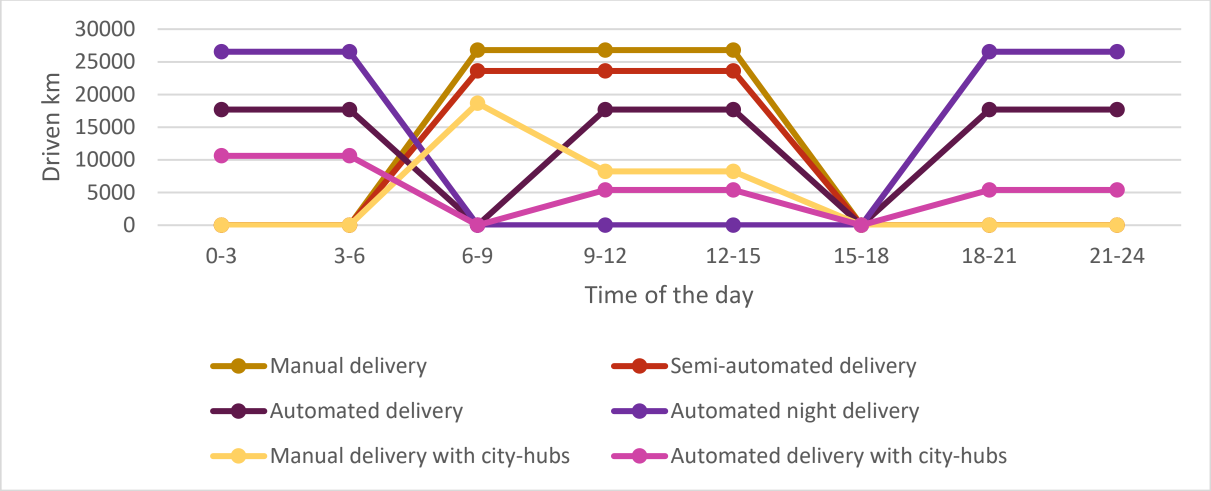


Figure 4.3: Chart for mileage (km) for each delivery scenario and breakdown to time of the day.

4.1.2.3 Hub-to-hub automated transport

Compared to the automated delivery SUC, the simulated area for the hub-to-hub SUC only considers a small area around the transfer hub, as illustrated in D7.3. Therefore, the effects of the transfer hub and the automation are much more visible. The results in Table 4.3 and Figure 4.4 show the results for the number of potential crashes. Especially during the transition phase between scenario A (no AVs) and scenario H (full transition to 2nd generation AVs) the number of potential crashes is significantly reduced with the automated freight trucks and transfer hub. This suggests that the additional benefit of this SUC is especially felt when human-driven vehicles are still on the road and at risk of crashing with (automated or non-automated) freight vehicles. Considering that this is an industrial area with a high number of heavy freight vehicles, this is a significant improvement for road safety.

Table 4.3: Number of potential crashes per 1000 vehicle km for the simulation scenarios.

Simulation scenario	A	B	C	D	E	F	G	H
	(100,0,0)	(80,20,0)	(60,40,0)	(40,40,20)	(20,40,40)	(0,40,60)	(0,20,80)	(0,0,100)
No transfer hub	2,6	2,9	3,2	2,9	2,6	2,3	1,7	1,0
With transfer hub	2,6	2,8	2,9	2,5	2,3	2,0	1,4	1,0

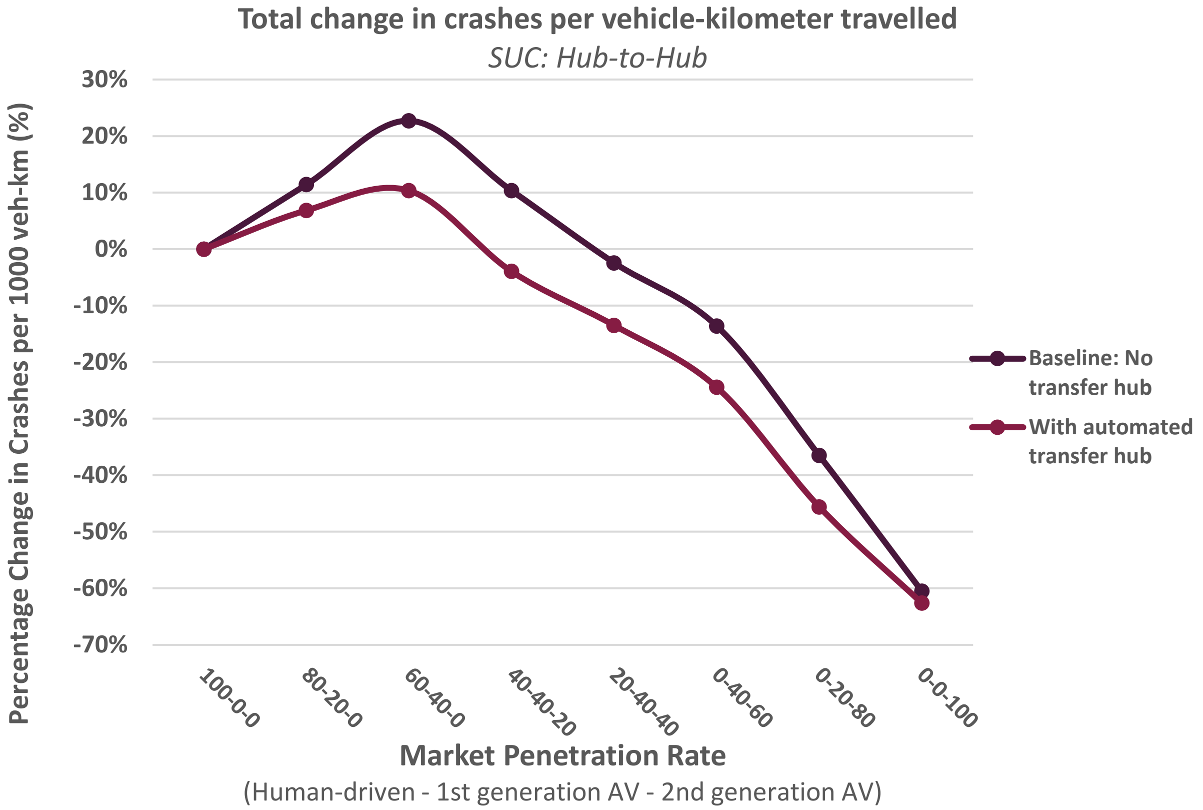


Figure 4.4: Predicted change in crashes per 1000 vehicle km for the simulation scenarios, measured in terms of percentage change from the respective starting scenario at a 0% penetration rate of automated vehicles

As with the other simulation scenarios, an initial increase in crash rates is predicted at lower penetration rates when there are still many interactions between human drivers and automated vehicles. While the reduction of the potential crashes due to the increasing AV penetration rate in the background traffic is visible by looking at the rows of Table 4.3 individually, the reduction by the transfer hub is visible by comparing the numbers in the same columns. As discussed in 4.1.2.1, this can be explained by the differences in driving styles and capabilities between the two populations which can lead to some higher risk conflicts between vehicles (e.g. headways which do not match the reaction times of human drivers). At higher penetration rates of automated vehicles, a significant reduction in crash rates is expected.

4.2 Emissions

4.2.1 Automated urban delivery

For the automated delivery and automated consolidation SUCs, we estimate the emissions caused by the freight vehicles based on the total driven kilometers presented in D7.2 (Hu et al., 2021). The impact on the overall emissions of the background traffic would be not visible since the share of the freight vehicles is too low. Therefore, we only consider the freight vehicles here.

We make the following assumptions for CO_2 emissions.

- Manual vans: The standard consumption of a diesel van is between 7.1 and 8.4 liters per 100 km. This corresponds to CO_2 emissions of 187 to 221 g/km. In the case of delivery trips, heavy stop-and-go traffic would have to be assumed, which according to Thomas et al. (2017) leads to up to 40% more fuel consumption and correspondingly higher CO_2 emissions. In this case, 309.4 g/km is be assumed.
- Manual trucks: The standard consumption for a 12-tonne truck is 21.4 liters per 100 km (diesel, Euro 6). This gives CO_2 emissions of 567.1 g/km (Webfleet solutions, 2020).
- AV vans and AV trucks: Electric and emission-free
- Delivery robots: Electric and emission-free

Table 4.4 shows the CO_2 emission rates under these assumptions. Note that the primary factor for these rates is i) the different mileages due to the different delivery scenarios and ii) the electrification rate of the delivery fleet. In LEVITATE we assume that all freight AVs will be electric and therefore emission-free while the manual freight vehicles use internal combustion engines fuelled by diesel, which is the standard at the moment. However, if we experience an adoption towards electric freight vehicles before the AV breakthrough, the manual delivery scenarios will effectively be at zero emissions locally as well. In case of mixed fleet scenarios where both diesel and AVs operate, the CO_2 emission rates will be proportional to the amount of diesel vehicles in the fleet.

Table 4.4: CO_2 emission rates per day for the delivery scenarios.

	Vans driven km	Vans CO_2	Trucks driven km	Trucks CO_2	Total CO_2
Manual delivery	80,389 km	24,8 t	-	-	**24,8 t**
Semi-automated delivery	70,805 km	0 t	-	-	**0 t**
Automated delivery	10,6177 km	0 t	-	-	**0 t**
Automated night delivery	10,6177 km	0 t	-	-	**0 t**

Manual delivery with city-hubs	24,675 km	7,6 t	10,445 km	5,9 t	**13,5 t**
Automated delivery with city-hubs	32,347 km	0 t	10,445 km	0 t	**0 t**

4.2.2 Hub-to-hub automated transport

As discussed in D7.3, the total mileage of the freight vehicles in the hub-to-hub automated transport remains constant with the introduction of the transfer hub. The main effects are due to the shift of freight traffic towards the night, resulting in a reduction of congestion and a reduction of potential crashes. Since the transfer hub is placed at the ramp area, the mileage overhead caused by changing manually operated trucks for AV trucks is minimal. Therefore, the changes in the CO_2 emission rates are neglectable.

4.3 Parking space

Parking space is considered as the required parking space in the city centre per person (m^2/person). The estimate of the impact of automation on parking space was made by using the Delphi method. The general experts’ opinion was that the introduction of automation in urban environment will reduce parking space required. More precisely, the introduction of AVs in the baseline scenario will lead to a reduction of -15,6% on parking space for 100% AVs market penetration rate. Regarding the automated freight transport interventions, fully automated delivery with night shifts only will reduce the most parking space required reaching -11,1% for 80% AVs market penetration rate. The introduction of hub-to-hub automated transfer and automated freight consolidation will not considerably affect parking space, since 1st round results indicated a maximum impact of 3,1% and -4,7% respectively. Finally, the introduction of fully automated delivery leads to a reduction of parking space which varies from -4,2% to -9,55 depending on the AVs market penetration rate.

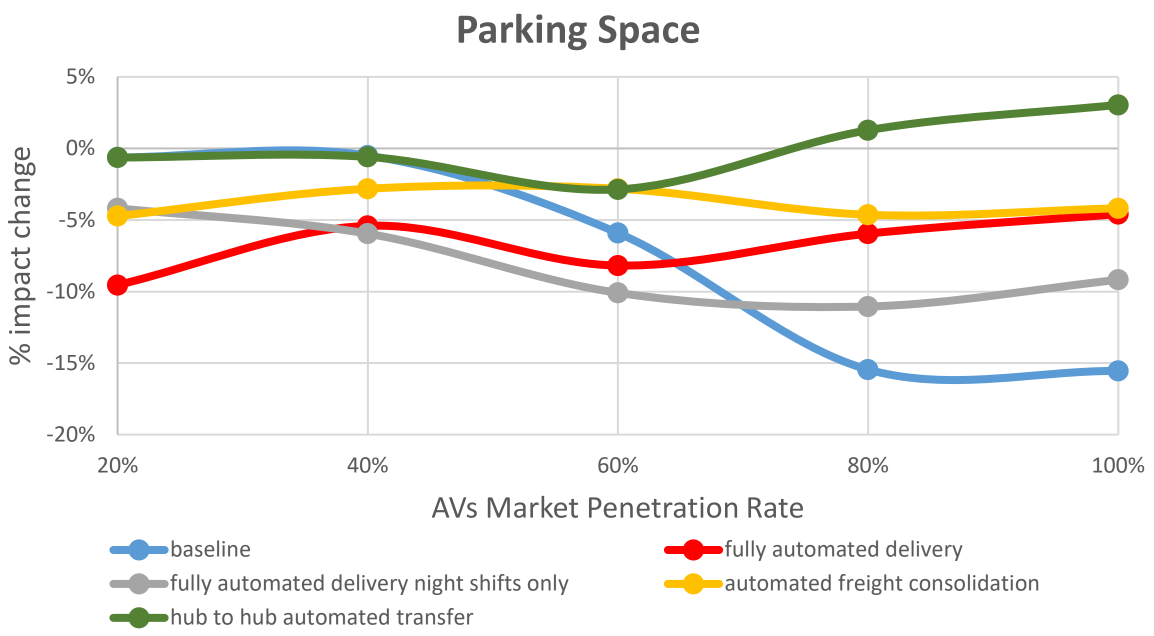
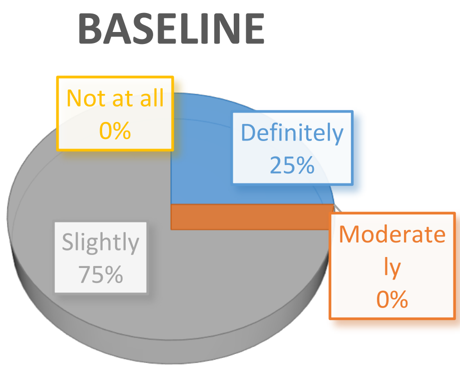


Figure 4.5: 1st round Delphi parking space results

The majority of the experts participating in the 2nd round stated that they slightly or not at all agree (50%-75%) with the resulted trends and only 25%-50% of experts agreed definitely or moderately with the 1st round results.



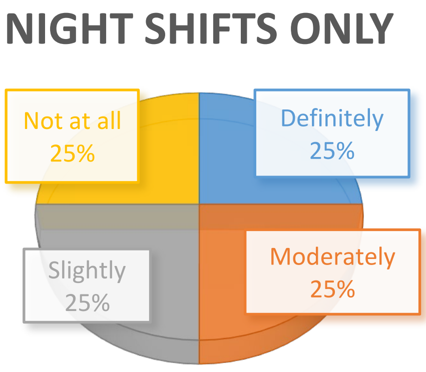


Figure 4.6: 2nd round Delphi results Baseline scenario

Figure 4.7: 2nd round Delphi results fully automated delivery with night shifts only

2nd round experts suggested that in fact all the studied scenarios will not considerably affect requirements for parking space, proposing average impacts of 0% to -5%. These suggestions have been taken into consideration in order to form the final coefficients to be introduced in the PST.

Table 4.4: Final PST coefficients for parking space

	Baseline		**Fully automated delivery**		**Fully automated delivery with night shifts only**		**Automated freight consolidation**		**Hub to hub automated transfer**	
AV penetration rates	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients
20%	-1,4%	0,986	-7,9%	0,921	-4,0%	0,960	-4,3%	0,957	-1,6%	0,984
40%	-1,3%	0,987	-4,6%	0,954	-5,4%	0,946	-2,8%	0,972	-1,5%	0,985
60%	-5,0%	0,950	-6,8%	0,932	-8,7%	0,913	-2,8%	0,972	-3,3%	0,967
80%	-11,5%	0,885	-5,1%	0,949	-9,4%	0,906	-4,2%	0,958	0,0%	1,000
100%	-11,6%	0,884	-4,0%	0,960	-7,9%	0,921	-3,8%	0,962	1,4%	1,014

4.1 Energy efficiency

Energy efficiency is defined as the average rate (over the vehicle fleet) at which propulsion energy is converted to movement (%). The impact on energy efficiency of the introduction of automation in the urban environment is calculated using the Delphi method. According to the results the introduction of automation in the urban environment will progressively improve energy efficiency. The baseline scenario will lead to an increase of 17,3% when AVs market penetration rate reaches 100%. Based on the 1st round answers the introduction of automated freight consolidation will improve energy efficiency the most reaching an increase of 26,4% for 100% AVs market penetration rate. The introduction of fully automated delivery with night shifts only, of hub-to-hub automated transfer and of fully automated delivery will all increase energy efficiency in the long-term reaching a maximum increase of 11,73%, 18,1% and 20,8% respectively.

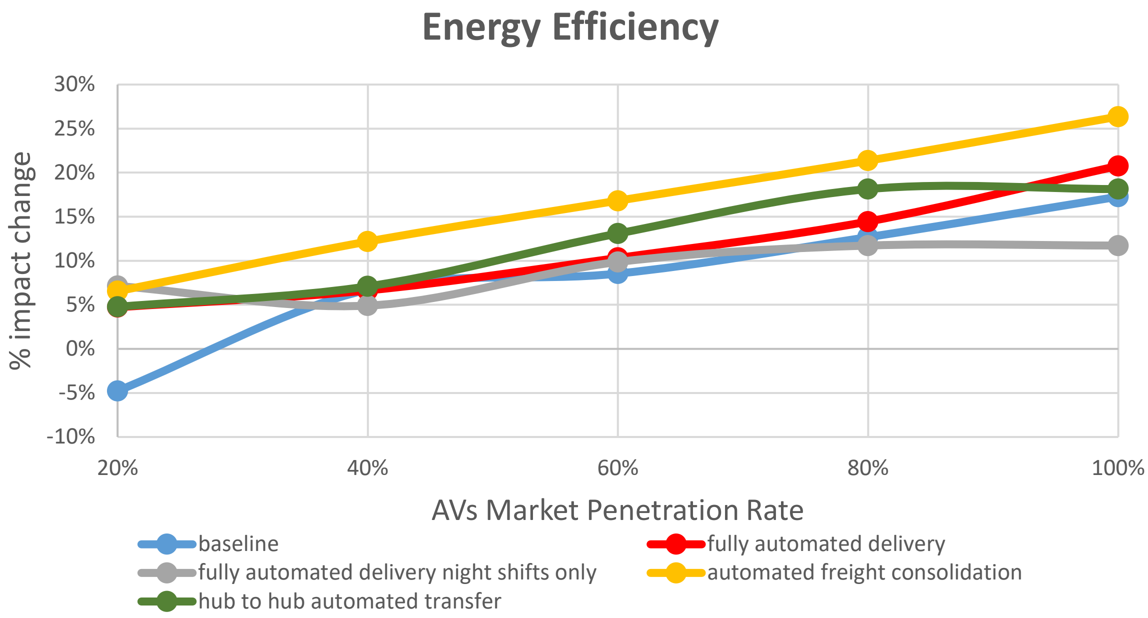


Figure 4.8: 1st round Delphi energy efficiency results

In the 2nd round the majority of experts agreed definitely (50%-75%) or moderately (0%-25%) with the 1st round results, but there were suggestions by 25% of the participants that the baseline scenario will not improve energy efficiency more than 10% and that the proposed automated freight transport interventions will all have an average improve of 15%-20%.

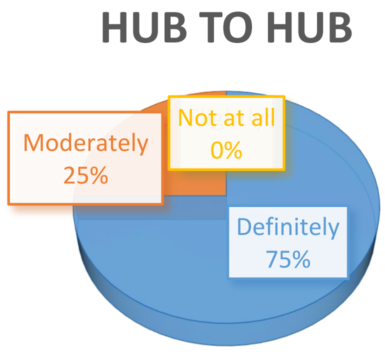


Figure 4.9: 2nd round Delphi results hub to hub automated transfer

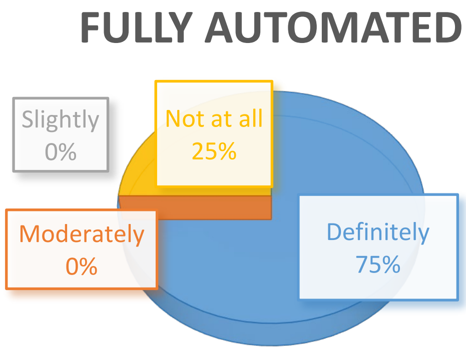


Figure 4.10: 2nd round Delphi results fully automated delivery

These suggestions were taken into consideration in the calculations of the coefficients to be introduced in the PST.

Table 4.5: Final PST coefficients for energy efficiency

	Baseline		**Fully automated delivery**		**Fully automated delivery with night shifts only**		**Automated freight consolidation**		**Hub to hub automated transfer**	
AV penetration rates	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients
20%	-3,7%	0,963	6,1%	1,061	7,7%	1,077	7,4%	1,074	5,6%	1,056
40%	6,5%	1,065	7,8%	1,078	5,7%	1,057	12,5%	1,125	7,8%	1,078
60%	8,2%	1,082	11,1%	1,111	10,1%	1,101	16,6%	1,166	13,5%	1,135
80%	11,9%	1,119	14,8%	1,148	11,8%	1,118	20,7%	1,207	18,2%	1,182
100%	16,0%	1,160	20,4%	1,204	11,8%	1,118	25,2%	1,252	18,2%	1,182

4.2 Public health

Public health (subjective rating of public health state, related to transport) is also an impact estimated using the Delphi method. The general experts' opinion in the 1st round was that all automated freight transport sub-use cases including the baseline scenario will lead to an improvement of public health, which is compatible with the reduced emissions resulted in micro-simulations as well as the experts' suggested improvement in energy efficiency (chapter 2.4). More precisely, the baseline scenario will improve public health the least reaching a maximum of 6,3%. Automated freight consolidation will have the biggest impact on public health for 100% AVs market penetration rate reaching an improvement of 20,4%. The introduction of fully automated delivery, of hub-to-hub automated transfer and fully automated delivery with night shifts only will all increase public health by 10%, 15% and 14,9% respectively.

There are several reasons for the assumption that automated freight will improve public health. First of all, CCAM in general has the potential to improve public health if proper policies and regulatory frameworks are implemented, since AVs will likely improve road safety and may help reshape cities to promote healthy urban environments (Rojas-Rueda et al. 2020). In addition, the local emissions caused by freight transport will be reduced to zero due to the assumption that AVs will be fossil-free. This might not be a direct contribution of vehicle automation since manual electric freight vehicles would have the same effect. However, the significant reduction of fleet operation costs by CCAM as shown in D7.2 (Hu et al. 2021) will accelerate the transition towards the emission-free automated freight logistics.

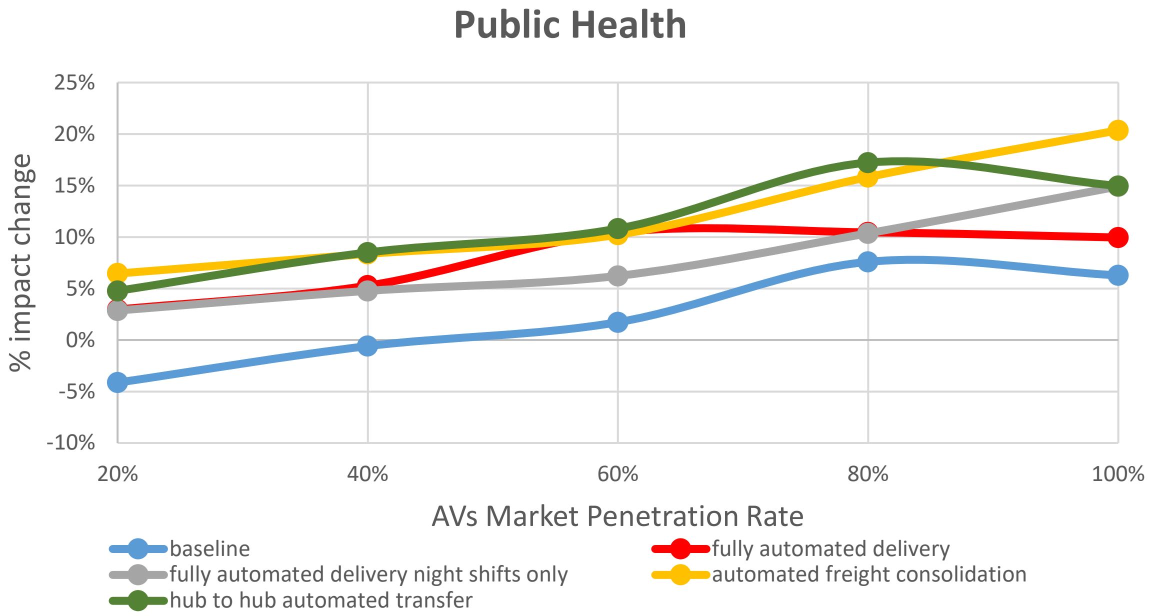


Figure 4.11: 1st round Delphi public health results

In the 2nd round the majority of experts commented that they agree definitely (50%) or moderately (0%-50%) with the resulted trends. 25% of the experts stated that they do not at all agree with the 1st round outcome for the baseline scenario, and proposed that automation will not improve public health but instead reduce it by 30%. Additionally, one expert suggested that all the automated freight transport scenarios will negatively affect public health by -20%. On the other hand, one expert suggested that all the freight transport scenarios will improve public health by an average of 25%.

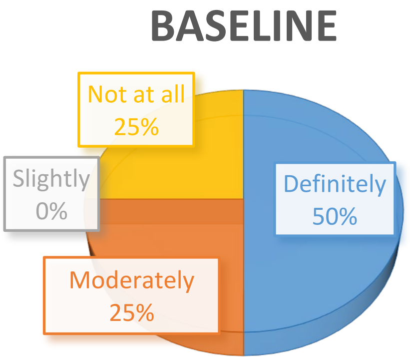


Figure 4.12: 2nd round Delphi results Baseline scenario

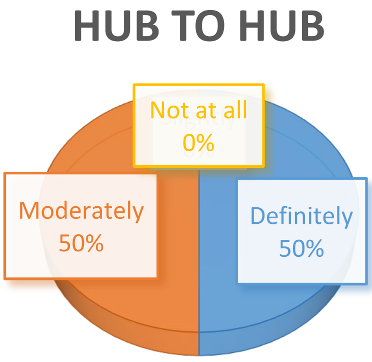


Figure 4.13: 2nd round Delphi results hub to hub automated transfer

These suggestions were taken into consideration in the calculations of the coefficients to be introduced in the PST.

Table 4.6: Final PST coefficients for public health

	Baseline		**Fully automated delivery**		**Fully automated delivery with night shifts only**		**Automated freight consolidation**		**Hub to hub automated transfer**	
AV penetration rates	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients	Aggregate change	PST coefficients
20%	-5,3%	0,947	2,9%	1,029	2,3%	1,023	6,0%	1,060	6,6%	1,066
40%	-2,1%	0,979	4,7%	1,047	3,8%	1,038	7,7%	1,077	10,0%	1,100
60%	0,0%	1,000	8,8%	1,088	4,9%	1,049	9,4%	1,094	12,0%	1,120
80%	5,2%	1,052	8,8%	1,088	8,2%	1,082	14,4%	1,144	17,8%	1,178
100%	4,0%	1,040	8,4%	1,084	11,8%	1,118	18,5%	1,185	15,7%	1,157

5 Conclusion and future work

5.1 Conclusions

In this deliverable, a combination of road safety assessment toolkit, micro-simulation, and operations research was applied to assess the impacts on road safety. The comprehensive section on road safety assessment discusses both qualitative and quantitative aspects. For the impacts such as change in driving behaviour and the interactions of delivery robots with VRUs, there are only few studies. Therefore, they are discussed in a qualitative manner. The quantitative results for the number of potential crashes are based on micro-simulation and Surrogate Safety Assessment Model (SSAM). They indicate consistently that with a higher AV penetration rate, the number of crashes per vehicle kilometer will decrease significantly when human driven vehicles are fully replaced by AVs. However, during the transition phase with a balanced mix between manual and automated vehicles, the crashes will rise temporarily compared to the status quo today. This result is consistent with the other use cases in LEVITATE on urban transport and passenger cars. Considering the automation of freight vehicles, the automated urban delivery SUC indicates that automated vans will reduce the number of potential crashes by 3% in average, and in the hub-to-hub automated transport SUC the automated trucks will reduce the number of potential crashes by 8% in average.

In the LEVITATE project, we made the general assumption that AVs are electric, i.e., they are either battery electric vehicles (BEV) or fuel cell electric vehicles (FCEV). While BEVs are reasonable for passenger cars and light commercial vehicles, FCEVs are attractive for heavy-duty vehicles (Çabukoglu et al. 2019). Both options have in common that with a higher AV penetration rate, the emissions will be proportionally lower. For freight transport, CO_2 emissions were considered for the freight vehicles for the automated delivery and automated consolidation SUCs. The impact on the overall traffic is small, since the share of freight traffic is low. For the freight vehicles, another primary influencing factor beside electrification is the mileage. Since the consolidation via city-hubs are effectively reducing the mileage by over 55% in our calculations, the potential for reducing emissions is huge, even if the drivetrain is not changed.

The wider impacts on parking space, energy efficiency and public health were based on a two-round Delphi panel. While the experts expected energy efficiency and public health to improve with the increasing AV penetration rate, the situation on parking space was mixed. From the Delphi results, the baseline scenario would decrease the demand for parking space with more AVs on the street. However, the automated freight transport measures such as automated delivery or hub-to-hub automated transport are expected to require more parking space than the baseline. This is an unexpected outcome, since freight consolidation will increase the efficiency by removing the redundancy of delivery system due to the white-label concept.

5.2 Future work

Foe the future, the limitations discussed for the road safety assessment should be considered. This requires other methodologies than operations research or micro-simulation, which only provide a theoretical estimation. For example, assessing the driving behaviour change would require a driving simulator or empirical studies with a mass of real-world data.

The wider impacts that were considered by the Delphi panel also require future work to put them in a more systematic view, where more details about the assumptions, scenario settings, and input data can be integrated. System dynamics will be the method of choice for modelling complex relationships.

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