Methods for cost-benefit analysis to support decision making

Deliverable D3.4 – WP3 – PU

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Work package 3, Deliverable D3.4

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List of abbreviations

AT Active transport (cycling and walking)
AV Automated vehicle
AUSS Automated urban shuttle service
BRT Bus rapid transport
CCAM Cooperative, connected and automated mobility
CAV Connected and automated vehicle
CBA Cost-benefit analysis
CPI Consumer price index
CS Consumer surplus (for transport passengers and manual passenger car drivers)
DCF Discounted cash flow
EEA European Economic Area
EC European Commission
EU European Union
GC Generalised costs (of travel)
GDP Gross domestic product
GHG Greenhouse gas
GLOSA Green light optimised speed advisory
HGV Heavy goods vehicle
INEA Innovation and Networks Executive Agency
LCV Light commercial vehicle
LRT Light rail transit (including tram)
MPR Market penetration rate
MRT Mass rapid transit (metro and other metropolitan railway)
NPV Net present value
NTS National travel survey
PDO Property damage only
PI Policy implementation
PKM (pkm) Passenger kilometre
PPP Purchasing power parity
PS Producer surplus (for transport service providers)
PST Policy support tool
PT Public transport
SB Shuttle bus
SDR Social discount rate
SUC Sub-use case
TKM (tkm) Tonne kilometre
VBTT Value of business travel time
VKM (vkm) Vehicle kilometre
VOC (voc) Vehicle operating cost
VSL Value of a statistical life
VTT Value of travel time
VTTS Value of travel time savings
WTP Willingness to pay

About LEVITATE

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

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

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

Specifically LEVITATE has four key objectives:

1. To incorporate the methods within **a new web-based policy support module** to enable city and other authorities to forecast impacts of CCAM.
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 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.
4. To apply the methods and **forecast the impact of CCAM** over the short, medium and long term for a range of use cases.

Executive summary

The objective of this deliverable is to provide documentation for the LEVITATE cost-benefit analysis (CBA) module. The CBA module was developed in Excel with the intent of subsequently being integrated in a comprehensive dynamic online Policy Support Tool (PST).

The purpose of the CBA module is to provide estimates of monetised effects of policy measures related to the introduction of Cooperative, connected and automated mobility (CCAM). The monetised benefits are compared to the costs of implementing the measures. The CBA takes into account the following effects (positive or negative benefits) that the CCAM policy measures might yield: changes in total amount of travel and modal split, travel time changes and changes in vehicle operation costs, changes in congestion, changes in emissions of local air pollutants (NO_x and PM_{10}) and CO_2, changes in no. of crashes, and changes in infrastructure space requirement (parking space).

Monetary valuations are based primarily on Elvik (2020), van Essen et al. (2019), and Wardman et al. (2016), with some few additional input sources.

The methodology follows CBA standards as per the EU guide to CBA of investment projects (Sartori et al. 2014), with some added input from national guides (e.g., Hagen et al. 2012).

The physical impacts estimated from baseline scenarios and the policy scenarios, the effects of total kilometre driven, travel time, emissions, conflicts, etc., are based on simulations in Levitate work packages WP5, WP6, and WP7, that are implemented within the Policy Support Module (PST) of WP8.

The CBA module will be set up as an extra module to the PST, meaning that after selecting scenarios and sub-use cases in the PST and seeing the results of that, one can choose to continue with the CBA. In the CBA, one must type in some extra information, e.g. the costs related to the selected sub-use case (CCAM policy measure). The CBA will compare the differences in impacts between a policy scenario and a reference (base) scenario, in monetary terms, and compare these estimated “benefits” of the policy against the cost of implementing the policy. The main CBA output is the estimated net benefit (benefits minus the implementation cost).

1 Introduction and objective

This deliverable describes the spreadsheet model for the cost-benefit analysis (CBA) module. It sets out the basis for the functionality of the CBA add-on module to the Policy Support Tool (PST). A few applications to particular sub-use cases (the CCAM policy scenarios), applying preliminary input data, will illustrate how the CBA works. This introductory chapter defines the objectives of the deliverable.

In addition to describing the functionality of the CBA add-on module in PST, in Levitate, the deliverable illustrates how CBA can be applied to CAV-related policies in general. The proposed approaches and valuations build to a large extent on established practices and are also applicable for other projects.

1.1 The LEVITATE project

LEVITATE (Societal level impacts of connected and automated vehicles) is a Horizon 2020 project which has the following main objectives:

1. 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.

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

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 module** to enable city and other authorities to forecast impacts of CCAM on urban areas. The methods developed within LEVITATE will be available within a module 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 3 and objectives of this deliverable

This deliverable contributes to the fourth objective; the CBA will be part of the policy support tool (PST).

Deliverable D3.1 (Elvik et al. 2019) provided a taxonomy of potential impacts of Cooperative, connected and automated mobility (CCAM) and briefly discussed how to measure the impacts. Deliverable D3.2 (Elvik et al. 2020) gave an overview of methods that can be used to predict and quantify potential impacts of connected and automated vehicles. Deliverable D3.3 (Elvik 2020) described how impacts of connected and automated vehicles could be converted to monetary terms, which most fundamentally rested on the possibility of quantifying the impacts (in physical terms). The objectives of the present deliverable, D3.4, comprise:

1. Provide a brief introduction to the methodology of CBA
2. Present an overview of the CBA module
3. Describe the CBA module elements related to different sub-use cases (policy scenarios)
4. Present some illustrative examples of how the CBA module works

The objective of the LEVITATE cost-benefit analysis module (CBA module) is to assess the effects of policy measures (sub-use cases) proposed in LEVITATE. These are measures for managing the introduction of connected and automated vehicles (CAVs), with the aim of utilising the technologies to achieve societal objectives. The measures comprise urban public transport, e.g., automated urban shuttles travelling between fixed stations, private cars, e.g., dedicated lanes for automated vehicles on urban highways, and freight, e.g., automated urban freight delivery.

The CBA module provides the possibility of monetising the impacts of the CAV policy measures, relative to baseline scenarios ("no policy" scenarios). The project horizon of the scenarios has a given, fixed underlying development in market penetration rate (MPR) for CAVs. The policy scenario and the reference (baseline scenario) are run for the same MPR.

The CBA module provides the possibility of monetising the impacts of the CAV policy measures, relative to a baseline scenario where no policy is implemented. The baseline scenario and the policy scenario have a fixed common underlying development in market penetration rate (MPR) for CAVs. Hence, in the calculations, the policy scenario and the baseline scenario are run with the same MPR.[1]

Policy measures will have an implementation cost, either an investment or some management costs, or both. Major expected impacts comprise congestion and travel time changes, and for some measures also changes in land use (i.e., replacing parking space). In CBA the impacts are monetised, yielding benefit changes of the policy measure that can be assessed against the implementation costs. The CBA will also enable comparison of the impacts across infrastructure users as well as for the policy entity (which implement the policy measures) and the local and global community.

[1] Thus, we disregard that policy measures might enhance the attractiveness of CAVs to the extent of possibly accelerating the MPR. But the impact of the policy measures may vary with regards to the MPR, thus varying over time.

Given the uncertainty of future changes and future effects of policy, the CBA module also includes functionalities for doing sensitivity analyses of variables that are specified or estimated in the LEVITATE project.

Finally, it should be stressed that all illustrations of the CBA module in this deliverable are based on preliminary input values. In many cases a literature-based fundament for proposed default values is provided. However, the values might be updated within LEVITATE, e.g., related to the sub-use cases or the underlying modelling of impacts. Part of the default values will also be amendable for the PST users.

1.3 What a CBA does

A CBA provides a comparison of the impacts that a policy measure is estimated to yield, in monetary terms, against the cost of carrying-out the policy measure (Broadman et al. 2018; Mishan & Quah 2020).[2] An economic or social CBA, is carried out from a societal perspective, as opposed to financial analysis (e.g., for a firm). CBA is based on an aggregation of individual preferences, whether these are revealed in markets or in other ways. E.g., the proposals for common transport-impact valuations in the EU have comprised survey-based valuations of travel time savings, emissions, and the prevention of transport fatalities/injuries (Bickel et al. 2006).[3]

Benefits and costs occurring in different years of the project horizon are brought together by use of discounting; costs and benefits that materialise in 2050 are worth less "now" than those materialising in 2025. Discounting of future monetary values enables an aggregation of costs and benefits over the whole project as "present values".

The net present value (NPV) of a project can be stated in a simplified way as:

$$\text{NPV} = \text{Present value of benefits} - \text{Present value of costs of implementation}$$

For a comparison of projects of different scale/scope, a benefit-cost ratio can be useful, but requires that only the cost of implementing policy is handled as "cost" and negative impacts handled as "negative benefits"):

$$\text{Benefit} - \text{cost ratio} = \frac{\text{Present value of benefits}}{\text{Present value of costs of implementation}}$$

When the NPV is positive (benefits are larger than the costs of implementing the policy measure), the benefit-cost ratio exceeds the value of 1.

[2] The method is also referred to as benefit-cost analysis. In one school of CBA terminology, the monetised impacts are termed "benefits", irrespective of their sign; thus, either «negative benefits» or disbenefits if the benefits are not positive; and "costs" are then confined to policy implementation costs (investments and management/maintenance, or start-up costs and running costs). However, in many applications the term "costs" will also refer to what is really "negative benefits", monetised effects that are due to some action or measure, e.g., "external costs". We apply a terminology where "costs" also might refer to "negative benefits".

[3] Such survey-based valuation methods are called stated-preference methods, also known as discrete choice experiments or contingent valuation (Bickel et al., 2006; Carson & Louviere, 2011).

The stream of benefits and costs over a project horizon of several years can also be assessed at a yearly basis, in addition to the aggregation over the entire project period. E.g., discounted benefits and costs can be shown for each project year as a "cash flow". Then the economic appraisal of policy interventions, the NPV estimation, can be described as the following:

$$\text{NPV} = -\text{Investment} + \text{cash flow}$$

In these terms, the cash flow measures the (change) in impacts over the time period (for the policy scenario vs. the baseline scenario); it represents benefits minus costs at each year of the project horizon.

An illustration is shown in Figure 1.1 below. It visualises how the alternative policy scenarios (implementing particular interventions / sub-use cases) fare in comparison to the baseline scenario ("do nothing" scenario) over time.

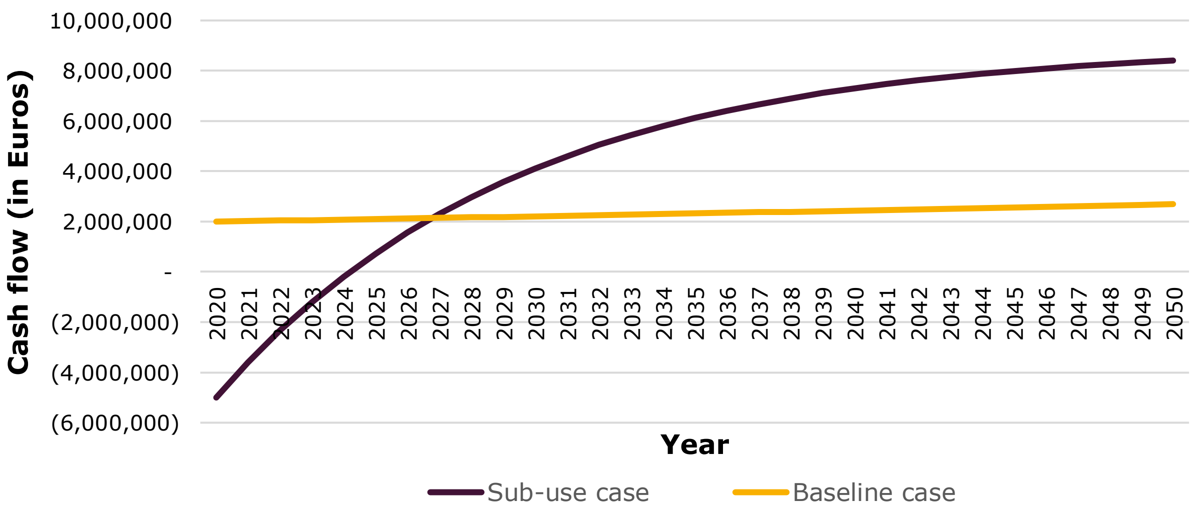

Figure 1.1: CBA illustration

The sub-use case has an initial negative cash flow, but over time the positive effects outweigh the negative effects. The total effect of the sub-use case is given as the sum of all the yearly effects for the baseline case and for the sub-use case. In this made up example, the sub-use case will clearly yield a positive total effect with respect to the baseline case.

2 Structure of the CBA module

This chapter describes how the CBA module is structured and which information it uses. The module builds primarily on the inputs/outputs already established within the PST but adds monetisation of impacts and requires some input from the user, estimated costs of implementing the sub-use case among others. The PST user can also adjust some of the inputs to the CBA module like valuations from national guidelines. The CBA comprises particular functionalities and economical calculations. Some of the proposed valuations in this chapter might be updated within LEVITATE.

Figure 2.1 illustrates the structure of the CBA module within the PST.

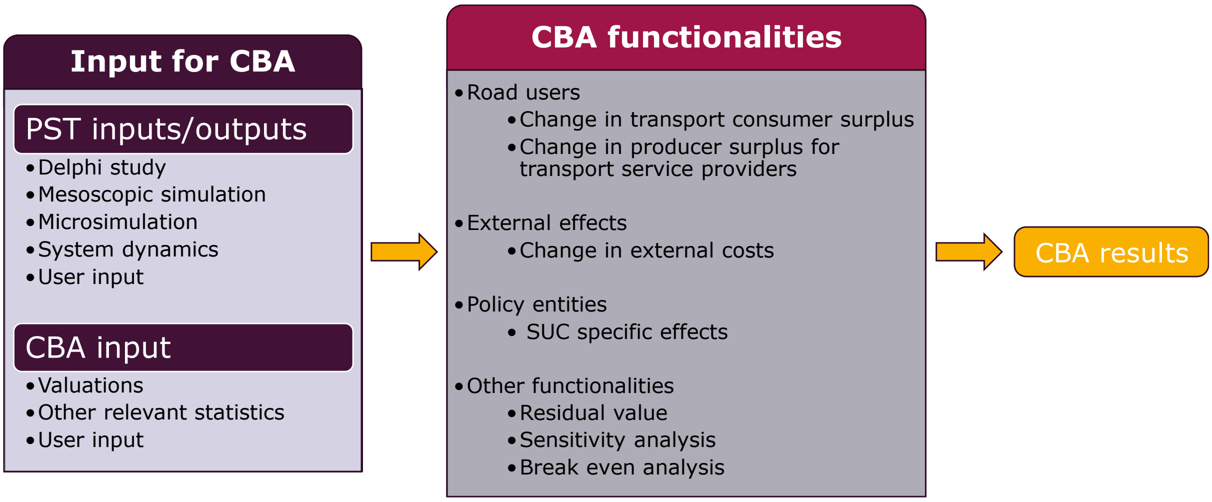

Figure 2.1: Structure of the CBA module

2.1 Input for CBA

The CBA module relies primarily on inputs that are either inserted into the PST (inputs) or produced within the PST (outputs). This comprises the specific case area and its gross domestic product (GDP), that sets the level for all default valuations of impacts in the CBA. Annual passenger kilometres or vehicle kilometres, average travel time, average delays, emissions of air pollutants and CO_2, as well as number of crashes, are also brought over from the PST to the CBA, for the baseline scenario(s) as well as the sub-use-case (policy) scenario(s). The sub-use cases will affect some of these variables, yielding differences between the policy scenario and the baseline scenario; the differences, or changes (impacts), that are valued monetarily (representing the benefits side) in the CBA.

Thus, the primary input additions to the CBA tool comprise the monetisation of the impacts. Another basic input to the CBA is the (social) discount rate for calculating the net present value of the measure, where we apply 3% as default (Sartori et al. 2014). The underlying default project period is 2020-2050, i.e., 30 years; for a later start year, set in the PST, say 2025, the CBA updates the project period to 2050-2025 = 25 years. Moreover, in the CBA module, the user can specify an end year different to 2050 (which is explained further below). The discount rate enables comparison of benefits and costs (cash flow) in the different years of the project period, irrespective of the length of the project period.[4]

The various types of inputs to the CBA are listed in the following.

2.1.1 PST inputs/outputs

The PST draws information from the following sources:

- **Mesoscopic simulation, microsimulation, and system dynamics**: Congestion/delay (sec/vkm), number of crashes, total distance travelled, NO_X, CO_2, PM_{10}, average commuting distance. The results from the microsimulation, mesoscopic simulation, and system dynamics can be found in several Levitate deliverables (Papazikou et al. 2020, Roussou et al. 2021a, 2021b, 2021c, Haouari et al. 2021, Sha et al. 2021, Chaudry et al. 2021, Hu et al. 2021a, 2021b, 2021c).

- **Delphi survey of experts**: Travel time, vehicle operating cost, freight transport cost, modal split (the market shares of public transport, passenger cars, and active transport, measured in passenger kilometres), vehicle occupancy, and parking space. The results from the Delphi study can be found in the same set of deliverables as referred to above.

- **Operation research**: Elements in freight transport inputs, that are also described in various Levitate deliverables (Hu et al. 2019, 2021a, 2021b, 2021c).

- **PST user input**: selection of use case (automated urban shuttle service, passenger car, or freight and logistics) baseline scenario, sub-use case "policy implementation" (PI), and location-specific information.

From decennial estimation or simulation results based on these methodologies, the PST provides annual growth rates for the whole project period, based on linear interpolations. This is provided for the different types of impacts: direct impacts, systemic impacts and wider impacts, for the baseline and the chosen PI.[5] The different impacts include total distance travelled in the given area, and subsequently the emissions, crashes, and more.

The size of the growth rates is based on the results from the abovementioned sources and these rates specify the yearly changes for the various impacts. They were estimated for a certain city or area (Zach et al. 2019a, 2019b, 2019c), and the PST assumes that the effects (in percent) are valid for all other cities or areas. This indicates the type of adaptability of the PST and the CBA module to location-specific user input.

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[4] The project period (T) and the discount rate (r) will, i.a., enter the formula for assessing total benefits and costs (the total cash flow) in annual terms, the present value annuity factor: $(1-(1+r)^{-T})/r$.

[5] In the following we use the terms "policy", "measure", "intervention", "intervention", and PI interchangeably with sub-use case.

The level and development of automation are shown by the market penetration rate (MPR), which comprises both the share of automated versus manual (human-driven, human-operated) and the distribution of automated between a 1st generation ("cautious") and a 2nd generation ("aggressive"). Eight different combinations of these three types of cars are specified (indicated by letters from A to H). In addition, there is a separate (and more rapid) market penetration rate for freight vehicles; such that for freight vehicles the MPR scenarios D-H are the same.

The following table shows the specification of the baseline scenarios, in terms of expected MPR in specific years, respectively for passenger cars and for freight vehicles.

Table 2.1: Market penetration rate (MPR) scenarios (A-H), for passenger cars and freight vehicles, under four different MPR scenario assumptions (expected year of MPR scenario).

	MPR scenario							
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Manual car	100%	80%	60%	40%	20%	0%	0%	0%
Automated car, 1st gen. (cautious)	0%	20%	40%	40%	40%	40%	20%	0%
Automated car, 2nd gen. (aggressive)	0%	0%	0%	20%	40%	60%	80%	100%
Manual freight vehicle	100%	80%	40%	0%	0%	0%	0%	0%
Automated freight vehicle	0%	20%	60%	100%	100%	100%	100%	100%
Optimistic	2020	2025	2030	2034	2038	2042	2046	2050
Neutral	2020	2028	2036	2044	2050			
Pessimistic	2020	2036	2045	2050				
No automation	2020-2050							

As shown in Table 2.1, it is assumed that the market penetration of automated vehicles will be faster for freight vehicles than for passenger cars. Freight vehicles are assumed to be 100% automated within the project horizon (2020-2050) under the optimistic (2034), neutral (2044) and pessimistic (2050) MPR scenario. For passenger cars, only the optimistic MPR scenario assumes 100% automated cars by 2050.

There are four types of baseline scenarios in terms of how fast (in which year) a specified MPR for automated cars and freight vehicles is reached: no automation, pessimistic, neutral, and optimistic. The PST user will select one of these four for the analyses in PST. That selected level of MPR over the project horizon is shared by the policy measure and the (no policy) baseline. The PST and CBA do not assess policies for influencing the MPR as such but accompanying policies (Papazikou et al. 2020).[6]

Table 2.2: provides an overview of PST inputs/outputs, structured as different types of impacts (see also Elvik 2020).

[6] The implicit assumption in the PST/CBA is then that the measures do not affect the level of automation in society.

Table 2.2: Utilised PST-variables in the various types of impacts

Direct impacts	Systemic impacts	Wider impacts
Travel time average duration of a 5km trip (by car) inside the city centre	*Amount of travel* person kilometres (pkm) of travel per year in an area	*Parking space* required parking space in the city centre per person
Vehicle operating cost direct outlays for operating a vehicle per kilometre of travel	*Congestion* average delays to traffic, in seconds per vehicle-kilometre (vkm), as a result of high traffic volume	*Road safety total effect* total number of crashes (for the given amount of travel)
Freight transport cost direct outlays for transporting a tonne of goods per kilometre	*Modal split, share of travel using public transport* % of travel amount made using public transportation	*NO_x due to vehicles* concentration of NO_x pollutants as grams per vehicle-kilometre (due to road transport only)
	Modal split, share of active travel % of travel amount made by cycle or by foot	*PM_{10} due to vehicles* concentration of PM_{10} pollutants as grams per vehicle-kilometre (due to road transport only)
	Vehicle occupancy rate average % of seats in use (passenger cars feature 5 seats)	*CO_2 due to vehicles* concentration of CO_2 as grams per vehicle-kilometre (due to road transport only)
		Commuting distances average length of trips to and from work (added together)

We will go into the details of how we handle these impacts in the next sub-section, also including the valuation of impacts.[7]

2.1.2 Basic handling of inputs

Default handling of transport modes

The PST comprises in general three classes of passenger transport modes: Public transport, passenger cars (manual and two types of automated, "1st generation" / "cautious" and "2nd generation" / "aggressive"), and active travel (cycle and walk). Some sub-use cases will include automated shuttle buses. Another set of sub-use cases will include automated freight vehicles.

Large parts of our input relate to other specifications of transport modes, and of manual types rather than automated. Regarding automated versus manual passenger cars, we draw primarily on Elvik et al. (2020) and Elvik (2020).

We apply the following default conventions:

[7] Among the specified direct impacts in the PST is also "access to travel", defined as the opportunity of taking a trip whenever and wherever wanted. It is an impact that has economic value, but within our CBA we do not find an appropriate handling of the Likert scale measurement in the PST. The same reasoning applies to "inequality in transport", among the wider impacts, defined as the degree to which transport services are used by socially disadvantaged and vulnerable groups. The "energy efficiency", among wider impacts, defined as the average rate over the vehicle fleet at which propulsion energy is converted to movement, is also omitted in the CBA.

- **Active travel** is handled as a simple average of cycling and walking, as a default in this deliverable (i.e., shares of 0.5 each, for cycle and for walk, in the joint active transport figures); in the CBA model we apply a generalised variable for the share of one mode, x=[0,1], such that the share of the other is y=1-x, so the shares can be easily adjusted.
- **Public transport** is handled as an urban European mix rail-based (45%) and road-based (55%), in terms of passenger kilometres (pkm). The rail-based is a balanced mix (15% of each) of tram/LRT, metro/subway, and other heavy rail (close to figures from UITP 2016 and Jagiełło et al. 2018). It is (implicitly) assumed that public transport, bus and rail-based, remains manual within the project horizon.[8]
- **Automated shuttle buses** will only be included under the urban transport sub-use cases. Automated shuttle buses will presumably represent new services (point-to-point public transport or on-demand shared taxi), not replacing former services (Roussou et al. 2019, 2021a). In cases where we lack particular information about shuttle buses, we either use data on (larger) buses or weighted averages of buses and cars (x=[0,1] and y=1-x).
- **Passenger car** distribution between manual, automated 1st generation ("cautious"), and automated 2nd generation ("aggressive") is given from the PST (via the MPR variable set). Automated ride-sharing cars are handled in a similar way as automated on-demand shuttles, as a type of (shared) taxi.
- **Freight vehicles**, manual and automated, will comprise heavy goods vehicles (HGV) and light commercial vehicles (LCV); and the freight MPR will indicate the shares of manual and automated freight vehicles, assumed to be equal for HGV and LCV. We also include "an average freight vehicle", a weighted average of HGV and LCV, in this deliverable. We set the default relative load share of HGV vs. LCV to 90%-10%, which by a 50-50 tonne km (tkm) freight share, between HGV and LCV, will yield a relative distribution of vehicle km (vkm) equal to 10% HGV and 90% LCV; but these shares are adjustable in the CBA model. We set a default freight share vkm of total road-based transport vkm equal to 10%.

It will in most cases be specified, in tables or text, how we adapt input from literature to the LEVITATE class of modes or to a specific LEVITATE vehicle type.

Basic handling of valuations

In the CBA module, we provide default valuations, but the user will have the opportunity to change them. Some of the default valuations can also be overruled by specific PST input (e.g., cost figures for automated vehicles, as well as particular input regarding automated shuttle buses and automated freight vehicles). The default valuations that we propose are based on various sources, including Deliverable 3.3 in LEVITATE (Elvik 2020), the European Handbook of External Costs (van Essen et al. 2019) and a meta-analysis of European travel-time valuations (Wardman et al. 2016).

The valuations provided will primarily represent EU-28 average values, stated in 2020-Euro prices (EUR_{2020}). The underlying GDP/capita for valuations in EUR_{2020} in EU-28 is

[8] Some large-scale "automated" rail-based systems already exist in Europe (see, e.g., Cassarino 2009).

approximately 30,500.[9] However, the initial GDP/capita in the PST, and subsequently the CBA module, is 17,000 EUR_{2020}. Thus, we present double set of the main valuations, both in EUR_{2020} for GDP/capita equal to 30,500 and in EUR_{2020} for GDP/capita equal to 17,000 (downscaled to 57% of the EU-28 average values).

2.2 Impacts in greater detail, including valuations

2.2.1 Direct impacts

Direct impacts are changes that are noticed by each transport/road user on each trip (Elvik 2020). These comprise travel time and the costs of operating/owning a vehicle or using transport. In the CBA, these impacts are differentiated with respect to the (included) transport modes. The valuation of travel time savings is also differentiated with respect to travel purpose.

Travel time, under congestion and free flow

Average travel time, passenger cars

As indicated above, to calculate average travel time (per km) for different transport modes, the first point of departure is the PST variable *travel time* – "*travel time (by car), in minutes per 5 km*". We assume that this travel time average ($h_{\text{min\_5km\_car}}$) is based on all passenger cars travelling within the given geographical area. The variable is defined in the same way, in the PST, whether the focus is on passenger cars, shuttle buses or freight vehicles.

Average delays, congestion

The second point of departure for the calculations of travel time is the PST variable *congestion* – "*average delays to traffic, in seconds per vehicle-kilometre (vkm)*". We assume that the average delay estimate ($d_{\text{sec\_km}}$) applies to passenger cars within the selected geographical area; it will also be assumed to apply to freight vehicles ($d_{\text{sec\_km\_car}} = d_{\text{sec\_km\_freight}} = d_{\text{sec\_km}}$). The definition of the variable will be the same whether the focus is on passenger cars, shuttle buses or freight vehicles. We will however assume a difference in the average delay between automated and manual vehicles, as we describe below.

A simplified fixed dichotomy of 75% free flow and 25% congestion

A third element that we apply in the CBA module is to simplify the distribution of traffic conditions to a dichotomy of free flow versus congestion. Elvik et al. (2020, p. 33) indicate that about 25% of the (road) travel is carried out under conditions that can be described by high traffic volume, or congestion (peak hours). Thus, the remaining 75% of the travel is occurring with lower traffic volumes or approximately free-flow conditions (off-peak hours). We use these estimates as our defaults.[10] Moreover, we assume that

[9] The EU-27 GDP/capita was 29,660 EUR_{2020}, according to Eurostat (http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_pc&lang=de, retrieved 11th of May 2021). The EU-28 GDP/capita is not stated for 2020, only for EU-27 (omitting the UK). However, based on differences between EU-27 and EU-28 in the foregoing years, an estimate of GDP/capita for EU-28 that is about 8-900 euro higher than for EU-27 seems reasonable.

[10] We are aware, of course, that the dichotomy free flow versus congestion is a somewhat gross simplification; e.g., that congestion can be classified into various levels. However, the PST variable, *average delays to traffic,*

the 25% congestion and 75% free flow apply to the vehicle kilometres (vkm, but also person km, pkm, and tonne km, tkm) that are transported; thus: $k_{\text{vkm\_cong}}$ and $\left(1 - k_{\text{vkm\_cong}}\right) = k_{\text{vkm\_flow}}$. The delay estimates from the PST ($d_{\text{sec\_km}}$) then applies only to the 25% of the vkm (and pkm and tkm) that occur under congestion.

<u>The travel time of the average car in free-flow and in congestion</u>
Utilizing the average overall travel time from PST, the delay per vkm from PST and our congestion vs. free-flow dichotomy, we can easily derive the average travel time for passenger cars in free-flow and in congestion:

$$h_{\text{min\_km\_flow\_car}} = h_{\text{min\_km\_car}} - \left(k_{\text{cong\_car}} * \left(\frac{d_{\text{sec\_km\_car}}}{60}\right)\right)$$

and

$$h_{\text{min\_km\_cong\_car}} = h_{\text{min\_km\_flow\_car}} + \left(\frac{d_{\text{sec\_km\_car}}}{60}\right)$$

Thus, if the average travel time for cars ($h_{\text{min\_km\_car}}$) is 3 min/km, the average travel time in free flow equals 3 minus the share of vkm in congestion ($k_{\text{vkm\_cong\_car}}$) times the average delay ($d_{\text{sec\_km\_car}}/60$). The average travel time in congestion is then equal to free-flow travel time plus the delay. The same formulas are applied to freight vehicles; and as the inputs are also the same, we derive the same average travel times, in free-flow and in congestion, for freight vehicles as for passenger cars.

Delay under congestion implies that the share of the travel time in congestion ($k_{\text{traveltime\_cong\_car}}$) is higher than the share of vkm ($k_{\text{vkm\_cong\_car}}$); it is higher than 25%. Applying formulas, we have that:

$$k_{\text{traveltime\_cong\_car}} = \frac{k_{\text{vkm\_cong\_car}} * h_{\text{min\_km\_cong\_car}}}{\left(k_{\text{vkm\_flow\_car}} * h_{\text{min \_km\_flow\_car}}\right) + \left(k_{\text{vkm\_cong\_car}} * h_{\text{min\_km\_cong\_car}}\right)}$$

The share of the travel time in free flow could be derived in the same way (we have in any case that: $k_{\text{traveltime\_flow\_car}} = 1 - k_{\text{traveltime\_cong\_car}}$).

<u>The travel time of manual and automated passenger cars and freight vehicles</u>
Automated vehicles are expected to contribute to improved exploitation of the existing infrastructure capacity. Elvik (2020, Ch. 4.4, p. 33) report findings of about 17% reduction in travel time under full automation. For simplicity, we assume that this effect grows linearly with the MPR over time; we decrease the automated vehicle travel time by 17% under congestion, relative to manual vehicles. Thus, $d_{\text{sec\_km\_autcar}} < d_{\text{sec\_km\_mancar}}$, but the weighted average remains the same ($d_{\text{sec\_km\_car}}$); and equivalently for freight vehicles. Travel time in free flow is assumed to be the same for automated and manual vehicles.

To derive the travel times in congestion, for automated and manual vehicles, we make use of their relative vkm shares ($s_{\text{vkm\_mancar}}$ and $s_{\text{vkm\_autcar}}$, for passenger cars, or or $T_{\text{mancar}}/T_{\text{car}}$ and $T_{\text{mancar}}/T_{\text{car}}$, where T refers to annual vkm for the mode; for cars, as for

in seconds per vkm, will to provide the measure of the congestion level (the average of various congestion levels). We still need to retain the dichotomy for the estimations of absolute (average) speed for various transport modes, in free-flow and in congestion.

active transport, relative vkm shares equal the relative pkm shares, in as much as the occupancy is the same in manual and automated cars). Applying formulas, we have that:

$$h_{\text{min\_km\_cong\_mancar}} = \frac{h_{\text{min\_km\_cong\_car}}}{s_{\text{vkm\_mancar}} + s_{\text{vkm\_autcar}} - (s_{\text{vkm\_autcar}} * 0.17)}$$

and

$$h_{min\_km\_cong\_autcar} = h_{min\_km\_cong\_mancar} - (h_{min\_km\_cong\_mancar} * 0.17)$$

The same formulas are applied for automated vs. manual freight vehicles. We do not differentiate between the 1st and 2nd generation of automated cars, thus we apply only the sum share of these ($s_{\text{vkm\_autcar}} = s_{\text{vkm\_aut1car}} + s_{\text{vkm\_aut2car}}$).

In general, the average delay will not be the same for manual cars and manual freight vehicles ($d_{\text{sec\_km\_mancar}} \neq d_{\text{sec\_km\_manfreight}}$) or between automated cars and automated freight vehicles ($d_{\text{sec\_km\_autcar}} \neq d_{\text{sec\_km\_autfreight}}$); but the weighted average remains equal ($d_{\text{sec\_km\_car}} = d_{\text{sec\_km\_freight}} = d_{\text{sec\_km}}$). That further implies that also the share of the travel time in congestion will vary. Different MPR of automated vehicles, between passenger cars and freight vehicles, explains these differences.

<u>The travel times for shuttles, public transport and active transport</u>
For shuttle buses and (other) road-based public transport we set the average travel times relative to passenger cars. Average travel time of buses relative to cars, in European city areas, will vary; but in general, the average travel time by bus can still be expected to be somewhat higher than travel time by car (Barter 1999). For simplicity we assume that the default average travel time in free flow is 20% higher by bus than by car.[11] The average delay for manual buses, in congestion, is assumed to be the same as for manual cars. We apply the same travel time assumptions for shuttle buses as for ordinary (large) buses; and we differentiate between manual and automated. Thus, for manual buses:

$$h_{\text{min\_km\_flow\_manbus}} = h_{\text{min\_km\_flow\_car}} * 1.2$$

and

$$h_{\text{min\_km\_cong\_manbus}} = h_{\text{min\_km\_flow\_manbus}} + \left({d_{\text{sec\_km\_mancar}}}/{60} \right)$$

For automated shuttle buses, we have that:

$$h_{\text{min\_km\_flow\_autshuttle}} = h_{\text{min\_km\_flow\_car}} * 1.2$$

and

$$h_{\text{min\_km\_cong\_autshuttle}} = h_{\text{min\_km\_cong\_manbus}} - (h_{\text{min\_km\_cong\_manbus}} * 0.17)$$

In general, the average delay, as well as the average share of the travel time in congestion, will not be the same for automated shuttle buses ($d_{\text{sec\_km\_autshuttle}}$) as for automated cars and automated freight vehicles.

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[11] This is close to estimates from Norwegian urban transport (Hjorthol et al. 2014).

We assume that rail-based public transport is not directly affected by LEVITATE sub-use cases. Thus, we can disregard variations in travel time variations in rail-based transport. However, there are indirect impacts in the CBA, as some sub-use cases might affect modal share; and this impact is also influenced by the share of rail-based versus road-based public transport. For simplicity we set the average travel time by rail equal to the free-flow average by car ($h_{\text{min\_km\_rail}} = h_{\text{min\_km\_flow\_car}}$), implicitly assuming no congestion effects.[12]

To enable overall (weighted) travel time calculations for public transport, we take a point of departure in the relative shares of person kilometres (pkm) for rail-based and road-based (bus) transport. We apply, respectively, 45% and 55% (see Table 2.16, in section 2.2.2), which is close to estimates from UITP (2016). As the travel time applies to the vehicle, we need to derive relative shares in vehicle kilometres (vkm) as well. Then we need the average occupancies in rail-based and bus transport; and we apply 85 for rail-based and 18 for buses (see Table 2.16). Dividing 45% by 85 and 55% by 18 yield relative vkm shares of 15% and 85%; the resulting vkm-weighted occupancy in public transport is 28 (Table 2.16).

When comes to active travel, we assume that these transport modes do not approach infrastructure capacity levels, such that the average travel time by cycle or on foot remains stable throughout the day. We apply, respectively, 4 min/km travel time for cycling and 12 min/km for walking; and with implicit 50%-50% shares (pkm and vkm), 6 min/km.[13]

Travel time estimations for the transport modes, for a given MPR scenario

The average travel times will vary with respect to the PST input variables, the average travel time and the average delay. For passenger cars and freight vehicles, the MPR of automated vehicles will also have an effect. Table 2.3 presents estimations based on the MPR scenario C (Table 2.1), including 40% automated cars and 60% automated freight vehicles. We apply 3 minutes as average travel time by car in the city centre (15 min per 5 km) and 200 seconds per km as average delay (for all cars and all freight vehicles).

[12] The average speed of some types of rail-based transport can be expected to be higher than that of cars (Barter 1999). The overall speed average depends on the location and the relative share of trams/LRT versus metro/MRT. Alexopoulos and Wyrowski (2015) found that the average speed of trams/LRT was about the same as for buses, while the metro/MRT clearly had higher speed (about 50-100% higher).

[13] These estimated average travel times for cycling and walking have been applied in Norwegian CBA, yielding, respectively 15 km/h and 5 km/h (NPRA 2018, p. 66). Walking and cycling speeds will vary with respect to individual characteristics, travel purpose, locations, etc., but an estimate of ca. 5 km/h for walking seems common (e.g., Weidmann 1992, Bosina & Weidman 2017). For cycling, estimated average speed will vary somewhat more, partly explained by variations in measurement approach; e.g., whether it is a door-to-door measurement (11.2 km/h, in Raser et al. 2018), a trip mesurement or a section measurement (respectively ca. 16.3 and ca. 19.1 km/h, in Flügel et al. 2017, as averages of their separate estimates for females and for males).

Table 2.3: Average travel times for different transport modes; assumptions and default estimates – MPR scenario C, 3 min/km average, and 200 sec/km delay

Transport mode	Default min/km (weighted average)	Default delay under congestion, sec/vkm	Assumed share of pkm and tkm under congestion	Estimated free-flow travel time, min/km, weighted average	Estimated congestion travel time, min/km, weighted average	Estimated share of travel time in congestion
Car, weighted average	3.00	200.00	*25%*	*2.17*	*5.50*	*45.80%*
Car, manual	*3.10*	*223.80*	*25%*	*2.17*	*5.90*	*47.50%*
Car, automated	*2.85*	*163.80*	*25%*	*2.17*	*4.90*	*42.90%*
Bus / shuttle bus, manual	*3.53*	*223.80*	*25%*	*2.60*	*6.33*	*44.80%*
Railed-based public transport	*2.17*	*0*	*0%*	*2.17*	*2.17*	*0%*
Public transport	*3.21*	*190.23*	*21.25%*	*2.54*	*5.71*	*37.80%*
Bus / shuttle bus, automated	*3.26*	*159.00*	*25%*	*2.60*	*5.25*	*40.20%*
Freight, weighted average	*3.00*	*200.00*	*25%*	*2.17*	*5.50*	*45.80%*
Freight, manual	*3.16*	*237.00*	*25%*	*2.17*	*6.12*	*48.50%*
Freight, automated	*2.90*	*174.60*	*25%*	*2.17*	*5.08*	*43.80%*
Active transport	*6.00*	*0*	*0%*	*6.00*	*6.00*	*0%*

Travel time estimates are applied in combination with the valuation of travel time savings (described below), with differentiation between free flow and congestion.[14]

Valuation of travel time savings

A European meta-analytic fundament

People are assumed to value (economically) the time spent in transport; they are willing to pay for reductions in their travel time. Wardman et al. (2016, Table 9) present meta-analytic estimates of valuations of travel time savings (VTTS), for different transport modes and travel purposes, based on sets of European valuation studies.[15] They applied GDP/capita adjusted for purchasing power parity (PPP), which takes into account that not only GDP but also cost levels vary across countries. Wardman et al. estimated VTTS for European states, not EU averages. We propose applying their estimates for Germany as a means for converting VTTS estimates from GDP-PPP/capita in EUR_{2010} (for Germany) to GDP/capita for EU-28 in 2020 in EUR_{2020} (30,500), and subsequently also downscaling to the initial default value in the PST/CBA (17,000).[16]

[14] Congestion also have external effects; but for the external effects we apply unit costs per vkm, thus we can use the fixed 25% directly, assuming equal occupancy levels in congestion and free flow, thus $k_{\text{vkm\_cong}} = k_{\text{pkm\_cong}} = 25\%$.

[15] VTTS will be a main driver of the resulting benefits of the Levitate sub-use cases. This section about default VTTS proposals for CBA will also provide an illustration of the GDP per capita-based approach within PST, that we described in sub-chapter 2.1.2.

[16] The cost levels, or PPP, in Germany, the largest national economy in the EU, have been fairly close to the EU average (according to the OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm, retrieved 11th of May 2021); thus the error in moving from GDP-PPP/capita to GDP/capita is limited.

Thus, based on the original VTTS estimates for Germany (Wardman et al. 2016, Table 9), we first apply the relative GDP-PPP/capita of EU-28 versus Germany, in 2010 (in EUR_{2010}), 24,500/26,107. That yields our GDP-based VTTS estimates for EU-28 in 2010.[17] The CPI-based updating from EUR_{2010} to EUR_{2020} yields slightly lower estimates than a (nominal) GDP-based updating for EU-28, from 2010 to 2020, applying 30,500/24,000.[18] In this deliverable, we will apply the estimates from the GDP-based updating, EU-28 – GDP/capita in EUR_{2020} (30,500). We also include estimates that are based on a 17,000/30,500 GDP-downscaling; the initial default levels in PST/CBA.

VTTS estimates for car travel, included directly from the European meta-analysis

Table 2.4 shows the resulting VTTS/hour estimates for (manual) cars ($w_{\text{hour\_mancar}}$), based on Wardman et al. (2016, Table 9).

Table 2.4: Default estimates of VTTS/hour; manual car

Mode of travel, travel purpose, and traffic condition	Value of travel time saving (VTTS) per hour				
	Germany - original values - GDP-PPP/capita in EUR_{2010} (26,107), GDP/capita in EUR_{2010} (31,942)	EU-28 - GDP-PPP/capita in EUR_{2010} (24,500), GDP/capita in EUR_{2010} (*24,000*)	EU-28 - Updating by CPI from EUR_{2010} to EUR_{2020}: 14.75%	EU-28 - GDP/capita in EUR_{2020} (*30,500*)	PST/CBA initial default GDP/capita in EUR_{2020} (17,000)
Car, commute, urban, free flow	7.48	*7.02*	*8.06*	*8.92*	*4.97*
Car, commute, urban, congested	10.64	*9.99*	*11.46*	*12.70*	*7.08*
Car, other purpose, urban, free flow	6.59	*6.18*	*7.09*	*7.85*	*4.38*
Car, other purpose, urban, congested	9.37	*8.79*	*10.09*	*11.17*	*6.23*
Car, business, urban, free flow	14.72	*13.81*	*15.85*	*17.55*	*9.78*
Car, business, urban, congested	20.93	*19.64*	*22.54*	*24.96*	*13.91*

Source: Wardman et al. (2016, Table 9, Germany).

Adapted VTTS estimates for public transport and active transport

We also need VTTS estimates for public transport and for active transport (cycling and walking). For road-based public transport we can apply the VTTS estimate for "bus, urban, commute" directly from Wardman et al. (2016, Table 9) as point-of-departure. That estimate can be considered a weighted average for travel under free flow and

[17] We are aware of the fact that EU was EU-27 in 2010, including the UK but not Croatia; and as Croatia had a GDP/capita and a GDP-PPP/capita below the average of the remaining EU countries, we slightly overestimate GDP/capita and GDP-PPP/capita in 2010 for the entity we term EU-28 (including both Croatia and the UK).

[18] Our estimates in EUR_{2020} are slightly below those proposed by Elvik (2020, Table 11), due to a small difference in the selected base for VTTS estimates in EUR_{2010} (Elvik 2020, Ch. 3.3.4). 14.75% is the product of the CPIs for each year in the EU-28 area (from 2010 to 2011, etc., up to 2020: 3.1%, 2.6%, 1.5%, 0.6%, 0.1%, 0.2%, 1.7%, 1.9%, 1.5%, 0.7%, according to Eurostat (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Consumer_prices_-_inflation, retrieved 11th of May 2021).

congestion. For car travel, Wardman et al. (2016) apply a VTTS multiplier (ω_{cong}) of 1.42 for congested vs. free flow. We propose applying the same differentiation for public transport, assuming a rounded 30% share of travel time in congestion (Table 2.3).[19] We also include VTTS estimates for rail, from the same source,[20] that also includes VTTS across travel purposes (Wardman et al. 2016, Table 12). We disregard congestion vs. free-flow variation in VTTS for rail-based transport.[21] Table 2.5 summarises the estimates for manual buses and rail-based modes.

Table 2.5: Default estimates of VTTS/hour; manual bus and rail-based transport

Mode of travel, travel purpose, and traffic condition	**Value of travel time saving (VTTS) per hour**				
	Germany - original values - GDP-PPP/capita in EUR2010 (26,107), GDP/capita in EUR2010 (31,942)	**EU-28 - GDP-PPP/capita in EUR2010 (24,500), GDP/capita in EUR2010 (*24,000*)**	**EU-28 - Updating by CPI from EUR2010 to EUR2020: 14.75%**	**EU-28 - GDP/capita in EUR2020 (*30,500*)**	**PST/CBA initial default GDP/capita in EUR2020 (17,000)**
Bus, commute, urban	5.68	*5.33*	*6.12*	*6.77*	*3.77*
Bus, commute, urban, free flow	*4.69*	*4.40*	*5.05*	*5.59*	*3.12*
Bus, commute, urban, congested	*6.66*	*6.25*	*7.17*	*7.94*	*4.43*
Bus, other, urban	5.01	*4.70*	*5.39*	*5.97*	*3.33*
Bus, other, urban, free flow	*4.14*	*3.89*	*4.46*	*4.94*	*2.75*
Bus, other, urban, congested	*5.88*	*5.52*	*6.33*	*7.02*	*3.91*
Bus, business, urban	11.18	*10.49*	*12.04*	*13.33*	*7.43*
Bus, business, urban, free flow	*9.24*	*8.67*	*9.95*	*11.02*	*6.14*
Bus, business, urban, congested	*13.12*	*12.31*	*14.13*	*15.64*	*8.72*
Rail, commute, urban	8.25	*7.74*	*8.88*	*9.84*	*5.48*
Rail, other, urban	7.27	*6.82*	*7.83*	*8.67*	*4.83*
Rail, business, urban	21.52	*20.20*	*23.18*	*25.67*	*14.31*

Source: Wardman et al. (2016, Tables 9 and 12, Germany).

Applying formulas, we have that:

$$w_{\text{hour\_manbus\_commute\_flow}} = \frac{w_{\text{hour\_manbus\_commute}}}{k_{\text{traveltime\_flow\_manbus}} + (k_{\text{traveltime\_cong\_manbus}} * \omega_{\text{cong}})}$$

and

[19] Actually, the share of travel time in congestion is *estimated* within the CBA module.

[20] Higher VTTS estimates for rail-based transport than for bus transport was a general pattern across various European studies; and for rail-based VTTS estimates, the same values were stated for urban (heavy) train transport as tram/LRT (Wardman et al. 2016, Tables 10 and 12). We also include metro in the overall rail-based VTTS category (Flügel et al. 2020).

[21] E.g., Fox et al. (2018) present slightly higher congestion multipliers of the VTTS for public transport. Rail-based transport is less prone to congestion than road-based transport, although extra trains in rush hours might cause congestion in the rail infrastructure as well; and trams/LRT might not be completely separated from the road transport. Moreover, what runs in parallel with congestion in public transport is crowding, that also affects VTTS (see, e.g., Wardman & Whelan 2011, Flügel et al. 2020).

$$w_{\text{hour\_manbus\_commute\_cong}} = w_{\text{hour\_manbus\_commute\_flow}} * \omega_{\text{cong}}$$

The calculations are equivalent for business and other travel purposes.

Regarding active transport, we might take a point-of-departure in the estimated VTTS multiplier for walking (ω_{walk}), in Wardman et al. (2016), 1.45 with respect to (manual) car travel in urban free-flow conditions.[22] They present no estimates for cycling, but we lean on Norwegian studies that have indicated somewhat lower VTTS estimates for cycling compared to walking, although higher than for motorised transport (Ramjerdi et al. 2010, Flügel et al. 2020); for simplicity we set the VTTS multiplier to the half for cycling (ω_{cycle}), compared to VTTS for walking, i.e., 1.225. If the km shares are 50%-50% for cycling and walking, the travel times of 4 min/km vs. 12 min/km imply a 25%-75% distribution of cycling travel time and walking travel time. The implicit VTTS multiplier for active transport (ω_{active}), w.r.t. manual cars, is then 1.394.

The following table summarises the vkm-weighted VTTS estimates for rail-based and road-based public transport as well as the weighted VTTS estimates for active transport (cycle and walk). VTTS for public transport is a weighted average of the VTTS for bus transport (85%) and VTTS for rail-based transport (15%).

Table 2.6: Default estimates of VTTS/hour; weighted estimates for public transport and active transport

Mode of travel, travel purpose, and traffic condition	**Value of travel time saving (VTTS) per hour**	
	EU-28 - GDP/capita in EUR2020 (*30,500*)	**PST/CBA initial default GDP/capita in EUR2020 (17,000)**
Public transport (road & rail), commute, urban, free flow	*6.23*	*3.47*
Public transport (road & rail), commute, urban, congested	*8.23*	*4.59*
Public transport (road & rail), other, urban, free flow	*5.50*	*3.07*
Public transport (road & rail), other, urban, congested	*7.27*	*4.05*
Public transport (road & rail), business, urban, free flow	*13.22*	*7.37*
Public transport (road & rail), business, urban, congested	*17.14*	*9.55*
Active transport, commute, urban	*12.43*	*6.93*
Active transport, other, urban	*10.94*	*6.10*
Active transport, business, urban	*24.46*	*13.63*

Applying formulas for VTTS for public transport, we have that:

$$w_{\text{hour\_public\_commute\_flow}} = s_{\text{vkm\_public\_rail}} * w_{\text{hour\_rail\_commute}} + \left(1 - s_{\text{vkm\_public\_rail}}\right) * w_{\text{hour\_manbus\_commute\_flow}}$$

The formula is equivalent for VTTS under congestion; and the calculations are equivalent for business and other travel purposes.

[22] Although in their case "walk time relates to time spent accessing/egressing a main mode on foot and not to walking as a mode in its own right" (Wardman et al. 2016, p. 94).

For active transport, the relative share of traveltime for cycle (versus walk) is:

$$s_{\text{traveltime\_cycle}} = \frac{s_{\text{vkm\_cycle}} * h_{\text{min\_km\_cycle}}}{s_{\text{vkm\_cycle}} * h_{\text{min\_km\_cycle}} + s_{\text{vkm\_walk}} * h_{\text{min\_km\_walk}}}$$

and the expression is equivalent for walking (and $s_{\text{traveltime\_walk}} = 1 - s_{\text{traveltime\_cycle}}$).

Moreover, for the VTTS/hour for walking and cycling, we set these from the VTTS/hour for manual car occupants (in free flow) using a fixed multiplicator (ω); e.g., for the VTTS/hour for walking:

$$w_{\text{hour\_walk\_commute}} = w_{\text{hour\_mancar\_commute\_flow}} * \omega_{\text{walk}}$$

and equivalently for cycle.

A travel time-weighted multiplicator for active transport can be derived as:

$$\omega_{\text{active}} = \omega_{\text{cycle}} * s_{\text{traveltime\_cycle}} + \omega_{\text{walk}} * s_{\text{traveltime\_walk}}$$

Thus, the VTTS/hour in active travel can be then derived using the multiplicator (ω_{active}):

$$w_{\text{hour\_active\_commute}} = w_{\text{hour\_mancar\_commute\_flow}} * \omega_{\text{active}}$$

The relative shares of cycle and walk are more important if the VTTS/hour differ substantially between cycling and walking.

Differentiating VTTS between manual and automated vehicles

Table 2.7 adds the differentiation of VTTS estimates with respect to the vehicles being human driven (manual) or automated.

Table 2.7: Default estimates of VTTS/hour; car and bus / shuttle bus, manual versus automated

Mode of travel, travel purpose, and traffic condition	Value of travel time saving (VTTS) per hour			
	EU-28 - GDP/capita in EUR2020 (*30,500*)		PST/CBA initial default GDP/capita in EUR2020 (17,000)	
	Manual vehicles	Automated vehicles	Manual vehicles	Automated vehicles
Car, commute, urban, free flow	*8.92*	*5.80*	*4.97*	*3.23*
Car, commute, urban, congested	*12.70*	*8.26*	*7.08*	*4.60*
Car, other, urban, free flow	*7.85*	*5.10*	*4.38*	*2.84*
Car, other, urban, congested	*11.17*	*7.26*	*6.23*	*4.05*
Car, business, urban, free flow	*17.55*	*11.41*	*9.78*	*6.36*
Car, business, urban, congested	*24.96*	*16.22*	*13.91*	*9.04*
Bus / shuttle bus, commute, urban, free flow	*5.59*	*4.75*	*3.12*	*2.65*
Bus / shuttle bus, commute, urban, congested	*7.94*	*6.75*	*4.43*	*3.76*
Bus / shuttle bus, other, urban, free flow	*4.94*	*4.20*	*2.75*	*2.34*
Bus / shuttle bus, other, urban, congested	*7.02*	*5.97*	*3.91*	*3.33*
Bus / shuttle bus, business, urban, free flow	*11.02*	*9.37*	*6.14*	*5.22*
Bus / shuttle bus, business, urban, congested	*15.64*	*13.29*	*8.72*	*7.41*

It is expected that automation of vehicles will lead to lower VTTS, reflecting improved comfort levels and, for car driving, the possibility of applying the time in the vehicle for other purposes than focussing on the driving. Following Elvik (2020, Ch. 4.4.1), we apply a downscaling to 65% for automated cars ($\omega_{\text{automation\_car}}$) and 85% for automated buses / shuttle bus ($\omega_{\text{automation\_bus}}$), relative to VTTS for manual vehicles.[23]

Applying formulas, we have, e.g., that:

$$w_{\text{hour\_autcar\_commute\_flow}} = w_{\text{hour\_mancar\_commute\_flow}} * \omega_{\text{automation\_car}}$$

and

$$w_{\text{hour\_autshuttle\_commute\_cong}} = w_{\text{hour\_manbus\_commute\_flow}} * \omega_{\text{automation\_bus}}$$

[23] Roussou et al. (2021a) propose setting the VTTS for shuttle bus riding to 75% of a private car's VTTS, with reference to publications by Fosgerau (2019) and Ho et al. (2016). In our case, the derived VTTS ratio between automated bus/shuttle and automated car is just above 80%, while it is just above 60% for manual buses vs. manual cars (

Table 2.7).

etc. For simplicity, we will treat all shuttle bus travel as having the same VTTS, whether it is point-to-point or on-demand (taxi). The same applies to ride-sharing (taxi) use of passenger cars; it is assumed to have the same VTTS as the average for travel by private passenger cars.

VTTS per vehicle kilometre (vkm)
We will need to transform VTTS/hour (w_{hour}) to VTTS/pkm (w_{pkm}) and then to VTTS/vkm (w_{vkm}). VTTS/vkm will be entered into the generalised cost of travel (GC). We apply the following type of formula to derive VTTS/pkm:

$$w_{\text{pkm\_autcar\_commute\_flow}} = \frac{w_{\text{hour\_autcar\_commute\_flow}}}{60} * h_{\text{min\_km\_flow\_autcar}}$$

To derive VTTS/vkm, we scale the expression by the occupancy ($n_{\text{occ\_autcar}}$, which is described below, under section 2.2.2).

$$w_{\text{vkm\_autcar\_commute\_flow}} = \left(\frac{w_{\text{hour\_autcar\_commute\_flow}}}{60} * h_{\text{min\_km\_flow\_autcar}}\right) * n_{\text{occ\_autcar}}$$

This is equivalent for all transport modes.

For passenger transport scenarios, the PST provides the total amount of travel in pkm. This is the sum of pkm in public transport, passenger car transport, and active transport. We obtain the sum of vkm, for each transport mode, by dividing by the occupancy. For freight transport scenarios, the PST provides the total amount of freight vehicle transport in vkm.

Travel purpose differentiation
As already specified, VTTS varies with respect to travel purpose as well as transport mode, in addition to the traffic conditions (Wardman et al. 2016). VTTS in commuting is somewhat higher than VTTS in other private travel purposes. Travel *during* work, for business purposes (not commuting), has the highest VTTS.[24]

To derive a weighted average VTTS across travel purposes, we need estimates of the shares of different travel purposes (business, commuting, other). Distributions of travel (or trip) purpose are presented in national travel surveys (see, e.g., Ahern et al. 2013). Although somewhat different approaches are applied across Europe, we have collected

[24] VTTS for business purposes involves a somewhat different approach, as it comprises both the valuation of the person (employee) travelling and the employer's valuation of the employee's use of time. Flügel et al. (2020, p. 13-15) applied the following version of a business-travel-time valuation model, which builds on Hensher (1977) and Batley (2015): VBTT=(1-*pq*)*MPL*+*VP*, where *q* is the share of saved travel time spent on work, *p* is the relative productivity when travelling (with respect to workplace productivity), *MPL* (wage plus non-wage costs minus labour-cost) equals the marginal labour productivity; thus (1-*pq*)*MPL* is the employers' valuation of travel time savings; and *VP* (≈VTTS) is the employee's (private) valuation of travel time savings. Flügel et al. (2020) present stated-preference surveys of travel time valuations, where they also asked the respondents how much of their business travel time was spent on work (q^*) and their perceived relative productivity (p^*), in the current situation without any autonomous vehicles. The average p^* per transport mode fluctuated around 0.8, while the average q^* varied considerably more across modes, from just over 10% for short-trip car driving to 40-50% for longer public transport trips. The product $p^* \times q^*$ was about 10-20% for car drivers (depending on the trip length), just above 20% for tram/metro passengers, 25-30% for passengers in cars, buses, airplanes, and 20-40% for train passengers. Thus, the more employees can work when travelling, $p \times q \rightarrow 1$, the less the employer values saving employees' business travel time, (1-*pq*)*MPL* decreases. Thus, both the employers' part and employees' part in VBTT can be expected to decrease as the share of autonomous vehicles increase.

some travel survey shares of commuting and business, putting all other purposes under "other". The following table summarises our findings.

Table 2.8: Travel purpose, estimations from European national travel surveys

Country	Population 2020 (millions)	Travel survey year	Business	Commuting	Other	Total
Germany	83.1	2017	11%	16%	73%	100%
UK	66.7	2019	3%	18%	79%	100%
Netherlands	17.3	2014-2015	6%	22%	72%	100%
Sweden	10.3	2006	3%	17%	80%	100%
Switzerland	8.6	2010	3%	29%	68%	100%
Denmark	5.8	2019	6%	18%	76%	100%
Finland	5.5	2011	4%	18%	78%	100%
Norway	5.4	2013-2014	2%	21%	77%	100%
Weighted average (%)	**SUM 202.7**		**7%**	**18%**	**75%**	**100%**

Sources: Ahern et al. (2013), Christiansen & Baescu (2020), DfT (2020), Hjorthol et al. (2014), Nobis & Kuhnimhof (2018), Thomas et al. (2018).

Based on the weighted averages of these EEA countries plus Switzerland, about 7% are business trips (travel during work) and commuting (travel to/from work) represents about 18% of the trips.[25]

However, the distribution of travel purposes will differ across transport modes as well. Estimates per transport mode are not readily available. If we take the recent Danish national travel survey (NTS) for 2019 as point-of-departure (Christiansen & Baescu 2020), we can propose weighted averages for transport modes, based on pkm modal share for each passenger transport mode, as specified in the following table.

Table 2.9: Default distribution of travel purpose for different transport modes

Transport mode	Business	Commuting	Other	Total
Active transport	1%	12%	87%	100%
Car	10%	16%	74%	100%
Public transport	3%	25%	72%	100%
Weighted average (%)	**7%**	**19%**	**74%**	**100%**

Sources: Christiansen & Baescu (2020) and own calculations based on Table 2.8.

The weighted averages of travel purpose shares, from the Danish study, are very close to the estimates in Table 2.8. Thus, according to the Danish NTS, passenger car travel had

[25] According to Eurostat (2018, p. 16): "Professional / business: Trip related to work but not considered as commuting" "Work (commuting): Work/commuting is first of all trips to the workplace at the location of the respondent's employer. Attending e.g. a meeting outside the address of the company is a business trip."

a higher relative share of business travel purpose ($s_{\text{business\_car}}$), compared to public transport and active transport ($s_{\text{business\_public}}$, $s_{\text{business\_active}}$). The relative share of commuting was highest for public transport. These figures can be applied as defaults for the travel purpose distribution per transport mode, subsequently yielding an average weighted VTTS per transport mode.

Applying formulas, we can derive travel-purpose weighted VTTS/hour, respectively for free flow and for congestion, e.g.:

$$w_{\text{hour\_mancar\_flow}} = w_{\text{hour\_mancar\_commute\_flow}} * s_{\text{commute\_car}} + w_{\text{hour\_mancar\_other\_flow}} * s_{\text{other\_car}} + w_{\text{hour\_mancar\_business\_flow}} * s_{\text{business\_car}}$$

and

$$w_{\text{hour\_autshuttle\_cong}} = w_{\text{hour\_autshuttle\_commute\_cong}} * s_{\text{commute\_public}} + w_{\text{hour\_autshuttle\_other\_cong}} * s_{\text{other\_public}} + w_{\text{hour\_autshuttle\_business\_cong}} * s_{\text{business\_public}}$$

etc. This will be equivalent for all transport modes. Moreover, we assume no difference in travel purpose distribution between automated and manual vehicles.

The following table summarises our weighted VTTS averages per transport mode, with differentiation with respect to travel condition (congestion vs. free flow). We also add overall estimates per transport mode, applying rounded congestions shares of travel time (50% for car and bus/shuttle, and 30% for road-based and rail-based public transport).[26] It is however the purpose weighted estimate for congestion and free flow, respectively, that we apply in the CBA.

Table 2.10: Default estimates of VTTS/hour; weighted averages for all travel purposes

Mode of travel and traffic condition	**Value of travel time saving (VTTS) per hour**			
	EU-28 - GDP/capita in EUR2020 (*30,500*)		**PST/CBA initial default GDP/capita in EUR2020 (17,000)**	
	Manual vehicles	**Automated vehicles**	**Manual vehicles**	**Automated vehicles**
Active travel	*11.25*		*6.27*	
Passenger car, free flow	*8.99*	*5.84*	*5.01*	*3.26*
Passenger car, congestion	*12.79*	*8.31*	*7.13*	*4.63*
Passenger car, all	*10.89*	*7.08*	*6.07*	*3.95*
Bus /shuttle bus, free flow	*5.28*	*4.49*	*2.94*	*2.50*
Bus /shuttle bus, congestion	*7.51*	*6.38*	*4.19*	*3.56*
Bus / shuttle bus, all	*6.40*	*5.44*	*3.57*	*3.03*
Public transport, free flow	*5.91*		*3.29*	

[26] As indicated above, the share of travel time in congestion, for every specified transport mode, can be estimated in the CBA module. This will be relevant for deriving the internal congestion costs, that are based on the addendum in VTTS combined with the delay; it enters the generalised cost of the travellers (passengers).

Public transport, congestion	*7.80*		*4.35*	
Public transport, all	*6.67*		*3.72*	

It is possible to allow the weighted VTTS for each transport mode to vary with respect to the distribution of travel purpose as well as the level of congestion (delay).[27] But some of these figures can also be set to fixed levels, e.g. the share of travel time in congestion. (See section 3.2.2 for application with multipliers.)

VTTS escalating over time

In our CBA we assume in general that the relative price levels remain fixed. However, Sartori et al. (2014) point to findings of an increase in VTTS relative to prices of goods/services in general – an escalating VTTS over time. Thus, they propose to model VTTS as increasing over time in proportion to real GDP increase per capita ($\Delta\text{GDP} - \text{infl}$). They indicate an elasticity value of 0.5 for non-work time and 0.7 for worktime. As the share of work-time travel (business) is very limited and not clearly delineated in our applications (and not part of the PST), we propose using (only) 0.5 as the common elasticity for all VTTS.[28]

Applying formulas, we have, e.g., that:

$$w_{\text{hour\_mancar\_flow}}^{2021} = w_{\text{hour\_mancar\_flow}}^{2020} + \left(w_{\text{hour\_mancar\_flow}}^{2020} * (\Delta\text{GDP} - \text{infl}) * 0.5\right)$$

In PST the suggested default value for real growth in GDP per capita is 0.5%; that is, a nominal growth of 1.5% minus the inflation of 1%. Thus, if VTTS grows by an elasticity of 0.5 with respect to GDP per capita, the VTTS growth factor will be 0.25% *per annum*. If the user changes the GDP per capita, the VTTS growth factor will be adjusted accordingly.

Vehicle operating (and ownership) costs per vkm

The weighted voc for private cars in the PST

The PST variable *vehicle operating cost* – "*direct outlays for operating a vehicle per kilometre of travel*" will yield a point-of-departure for default operating (and ownership) costs in the CBA. We assume that this cost figure applies to the weighted average of manual and automated cars ($c_{\text{voc\_vkm\_car}}$); and we assume that it covers operating costs (fuel, maintenance/repairs) as well as ownership costs, the latter comprising depreciation and insurance costs (Elvik 2020, Hu et al. 2021a).[29] The operating (and ownership) costs for automated cars are assumed to be two thirds (67%) of those for manual passenger cars ($c_{\text{voc\_vkm\_autcar}} = 0.67 * c_{\text{voc\_vkm\_mancar}}$).[30] The weighted average will depend on the

[27] For public transport, the rail-based part of VTTS has been purpose-weighted in the same way as for bus transport, applying the same public transport weights from Table 2.9.

[28] A similar approach is proposed for VTTS in CBA in Norway; the value of a statistical life and possibly other valuations of health and environment can also be expected to escalate over time (Hagen et al. 2012).

[29] Elvik (2020) proposes an estimate of about 0.15 €/km in vehicle operating costs for passenger cars, covering fuel, tyre wear, and reparations/maintenance. The estimate for ownership cost, by Elvik (2020) is 0.138 €/km.

[30] The cost relationship can be derived from the operating cost estimate in 2050 in an optimistic scenario (thus 100% automated cars in 2050) compared to a scenario of no automation.

shares of automated (s_{autcar}) and manual (s_{mancar}) cars. For a given vehicle operating cost in the PST, we can derive the costs for manual cars as:[31]

$$c_{\mathrm{voc\_vkm\_mancar}} = \frac{c_{\mathrm{voc\_vkm\_car}}}{s_{\mathrm{mancar}}+0.67 * s_{\mathrm{autcar}}}$$

In the following we assume 0.26€/km to be the default PST vehicle operating (and ownership) cost (voc). Moreover, we assume that the underlying MPR baseline scenario level is "scenario C" (Table 2.1), implying 60-40-0 distribution of manual cars, automated 1st gen., and automated 2nd gen. Applying the formulas above, we then derive 0.30€/km (set according to the default PST/CBA GDP/capita of 17,000 EUR_{2020}, equivalent to 0.54€/km according to the EU-28 GDP/capita average of 30,500 EUR_{2020}). The vehicle operating and ownership cost for automated cars is then 0.20€/km (equivalent to 0.36€/km according to the EU-28 GDP/capita average of 30,500 EUR_{2020}).

<u>Derived voc for specific freight transport</u>
For freight transport, our point of departure is the default operating and ownership costs derived for light commercial vehicles (LCV) applied in delivery, presented by Hu et al. (2021a). We assume the EU-28 cost level of GDP/capita average of 30,500 EUR_{2020} as the appropriate underlying cost level for these figures. The setup by Hu et al. shows how vehicle operating and ownership costs can be derived from various cost inputs, the acquisition price, the vehicle use, fuel costs, and costs of maintenance and insurance costs. The acquisition is brought to annual costs by a simple linear depreciation of the price and the vehicle's useful years of life (and zero salvage value). We include the cost of personnel; although autonomous vehicles have no drivers, their operation might need monitoring personnel (Hu et al. 2021a). We propose figures for HGV based on a simple scaling factor of three (for acquisition, maintenance, insurance, and fuel consumption), with respect to LCV costs. Table 2.11 summarises the default annual cost figures for manual and autonomous LCVs and HGVs.

Table 2.11: Vehicle cost figures for deriving vehicle operating and ownership costs for freight vehicles, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

Cost element	**LCV (LGV, van)**			**HGV (truck)**	
	manual	**semi-auto**	**full auto**	**manual**	**automated**
Vehicle acquisition	€30,000	€50,000	€70,000	*€90,000*	*€210,000*
Years of useful life	10	10	10	*10*	*10*
Annual mileage (vkm) per vehicle	*13,940*	*15,340*	*27,670*	*25,000*	*35,000*
Depreciation	€3000	€5000	€7000	€9000	€21,000
Fuel consumption	0.0956 l/km	0.1805 kWh/km	0.1805 kWh/km	*0.29* l/km	*0.54* kWh/km
Fuel price per litre or per kWh	€1.5	€0.1	€0.1	€1.5	€0.1
Fuel (annual per vehicle	€2000	€280	€500	*€10,800*	*€3800*
Maintenance (annual per vehicle)	€1000	€1000	€1000	*€3000*	*€3000*
Insurance (annual per vehicle)	€2000	€1720	€1500	*€6000*	*€4500*
Delivery robot fleet			*€12,000*		

[31] Obviously, if the share of manual cars (s_{mancar}) is 100%, the derived vehicle operating and ownership cost for manual cars is equal to the PST variable; and equivalently for the opposite case of a 100% MPR of automated cars (s_{autcar}).

Personnel per vehicle (delivery or monitoring)	€45,500	€45,500	€12,000	*€45,500*	*€12,000*
Annual cost vehicle (not including personnel costs)	€8000	€8000	€10,000	*€28,800*	*€30,400*
Annual cost total	€53,500	€53,500	€34,000	*€74,300*	*€42,400*

Source: Hu et al. (2021a) for LCV (delivery vans) and own calculations for HGV.

The coloured cells in Table 2.11 indicate which input figures would be needed for deriving the figures in the non-coloured cells. At the outset we assume a fossil fuel price of 1.5€/litre and an electricity price of 0.1€/kWh, consistent with PST defaults. The vehicle operating and ownership costs (voc) per vkm can be derived from the annual figures in Table 2.11, simply dividing annual costs by the annual mileage.

Table 2.12: Vehicle cost figures for deriving vehicle operating and ownership costs for passenger vehicles, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

Cost element	**Automated shuttle bus**			**Bus (large)**	**Passenger car (5 seats)**	
	10 seats	**8 seats**	**15 seats**		**manual**	**autom. 1st & 2nd gen.**
Vehicle acquisition	*€60,000*	*€50,000*	*€70,000*	*€130,000*	*€30,000*	*€40,000*
Years of useful life	*10*	*10*	*10*	*10*	*15*	*15*
Annual mileage (vkm) per vehicle	*20,000*	*10,000*	*10,000*	*25,000*	*12,000*	*15,000*
Depreciation	€6000	€5000	€7000	€13,000	€2000	€2670
Fuel consumption	*0.20* kWh/km	*0.18* kWh/km	*0.22* kWh/km	*0.3* l/km	*0.08* l/km	*0.13* kWh/km
Fuel price per litre or per kWh	€0.1	€0.1	€0.1	€1.5	€1.5	€0.1
Fuel (annual per vehicle	*€300*	*€270*	*€330*	*€21,530*	*€1440*	*€200*
Maintenance (annual per vehicle)	*€1000*	*€1000*	*€1000*	*€3000*	*€1000*	*€1000*
Insurance (annual per vehicle)	*€1200*	*€1200*	*€1200*	*€4500*	*€2000*	*€1500*
Personnel per vehicle (bus or taxi driver)	*€0*	*€0*	*€0*	*€45,500*	*€45,500*	*€0*
Annual cost vehicle (not including personnel costs)	*€8500*	*€7470*	*€9530*	*€31,750*	*€6440*	*€5370*
Annual cost total	*€8500*	*€7470*	*€9530*	*€77,250*	*€51,940*	*€5370*

Table 2.12 shows a similar set-up for deriving voc for passenger vehicles. The cost elements are primarily illustrative, but do retain some of the common costs with those

stated for freight vehicles, e.g., fuel costs (Hu et al. 2021a).[32] The cost levels for freight vehicles can provide yardsticks for the cost levels for buses and shuttles.[33] For passenger cars, the combination of annual cost figures is such that the resulting voc/vkm is equal to the PST defaults.

Default vehicle operating and ownership costs (voc) per vkm

Table 2.11 and Table 2.12 list annual costs per vehicle. Dividing the total by the annual mileage yields the vehicle operating and ownership costs per vkm (

[32] Probably the cost relationship between manual and automated cars will change over time. Some relatively recent sources considered ownership costs as relatively higher for automated cars (Laizāns et al. 2016, NPRA 2018), but that might change in a situation where a large share of automated vehicles have penetrated the market. E.g. Maibach et al. (2006), Laizāns et al. (2016), and NPRA (2018) also present operating and ownership cost estimations.

[33] If automated shuttles will be an entirely new type of policy intervention, a service that do not replace a former service, then the cost figures for operating and own shuttles could be placed under the costs of the intervention. However, in the CBA we handle the shuttles in the same way as other modes, such that (changes in) vehicle operating and ownership costs are monetised impacts, implicitly on the benefit side of the CBA.

Table 2.13). As indicated, the voc/vkm for passenger cars are the PST defaults. The figures for LCV freight vehicles follow Hu et al. (2021a, b). The voc/vkm for other vehicles results from the combination of assumed annual cost levels and assumed mileage. The weighted voc/vkm averages of freight vehicles (LCV plus HGV) are based on the following: the default relative load capacity of HGV vs. LCV is set to 9-1 and the shares of tkm transported are equal between HGV and LCV (50%-50%); that yields 90% of vkm by LCV versus 10% by HGV.[34]

For active transport we apply zero voc for walking; and for cycle we set voc to a relative share of the voc for manual cars, i.e., 20% (Litman & Doherty 2011). For rail-based transport we apply a total cost estimate based on an average of estimates presented by Gatusso and Restuccia (2014), updated to updated to EUR_{2020}. This estimate is consistent with figures presented by Steer Davies Gleave (2015). We assume that the same cost levels apply to all types of rail-based transport (from trams to metro and other heavy trains). As before, the overall road and rail public transport estimate is a vkm-weighted average of rail-based (15% as default) and bus (85% as default).

The voc/vkm estimates in

[34] This is based on Vienna figures, and it might be appropriate for other European city areas, but for intercity freight transport the share of HGV vkm is supposedly higher vis-à-vis LCV.

Table 2.13 provide relative cost differences between transport modes from which we can derive voc multipliers (ω_{voc}). In the CBA module we apply fixed multipliers to derive voc for all other passenger transport modes than voc for cars; the voc for cars is derived directly from the PST (*vehicle operating cost*, $c_{\text{voc\_vkm\_car}}$) under passenger transport scenarios.

Table 2.13: Derived average vehicle operating and ownership costs, for 0.26 EUR$_{2020}$/vkm in PST

Transport mode	**EU-28 - GDP/capita in EUR$_{2020}$ (30,500)**							**PST/CBA initial default GDP/capita in EUR$_{2020}$ (17,000)**	
	Vehicle operating (fuel, main-tenance)	**Insu-rance**	**Deprec-iation**	**Sum without person-nel costs**	**Person-nel**	**Sum total, per vkm**	**Sum total, per pkm or tkm**	**Sum, total, per vkm**	**Sum total, per pkm or tkm**
Car, weighted average (in PST)								***0.26***	*0.21*
Car, manual	*0.20*	*0.17*	*0.17*	*0.54*		***0.54***	*0.43*	***0.30***	*0.24*
Active travel						*0.05*	*0.05*	*0.03*	*0.03*
Bus, manual	*0.57*	*0.18*	*0.52*	*1.27*	*1.82*	*3.09*	*0.17*	*1.72*	*0.10*
Railed-based public transport						*15.00*	*0.18*	*8.36*	*0.10*
Public transport (weighted rail-bus average)						*4.88*	*0.17*	*2.72*	*0.10*
HGV, manual	*0.56*	*0.24*	*0.36*	*1.16*	*1.82*	*2.98*	*1.57*	*1.66*	*0.87*
LCV, manual	*0.22*	*0.14*	*0.22*	*0.58*	*3.26*	*3.84*	*18.51*	*2.14*	*10.31*
Freight, manual (weighted average)	*0.25*	*0.15*	*0.23*	*0.64*	*3.12*	*3.75*	*9.97*	*2.09*	*5.55*
Automated car	*0.08*	*0.10*	*0.18*	*0.36*		***0.36***	*0.29*	***0.20***	*0.16*
Automated shared car (taxi)				*0.36*		*0.36*	*0.18*	*0.20*	*0.10*
Automated on-demand shuttle, 8 s. (taxi)	*0.12*	*0.12*	*0.50*	*0.74*		*0.74*	*0.19*	*0.41*	*0.10*
Automated on-demand shuttle, 15 s. (taxi)	*0.12*	*0.12*	*0.70*	*0.94*		*0.94*	*0.13*	*0.52*	*0.07*
Automated point-to-point shuttle, 10 s.	*0.07*	*0.06*	*0.30*	*0.43*		*0.43*	*0.09*	*0.24*	*0.05*
Automated HGV	*0.14*	*0.13*	*0.60*	*0.87*	*0.34*	*1.21*	*1.01*	*0.67*	*0.56*
Automated LCV	*0.05*	*0.05*	*0.25*	*0.35*	*0.87*	*1.22*	*9.21*	*0.68*	*5.14*
Automated freight (weighted average)	*0.06*	*0.06*	*0.29*	*0.40*	*0.82*	*1.22*	*5.09*	*0.68*	*2.84*
Semi-automated LCV	*0.08*	*0.11*	*0.33*	*0.52*	*2.97*	*3.49*	*14.76*	*1.95*	*8.25*

For manual buses and weighted average public transport (bus and rail-based), cycles and weighted average active transport, we apply multipliers with respect to manual cars ($c_{\text{voc\_vkm\_mancar}}$). For automated shuttles we apply multipliers with respect to automated cars ($c_{\text{voc\_vkm\_autcar}}$). Thus, e.g., for an automated shuttle with 8 seats we derive voc as:

$$c_{\text{voc\_vkm\_autshuttle8}} = c_{\text{voc\_vkm\_autcar}} * \omega_{\text{voc\_autshuttle8}}$$

and, furthermore, for manual buses:

$$c_{\text{voc\_withpers\_vkm\_manbus}} = c_{\text{voc\_vkm\_mancar}} * \omega_{\text{voc\_withpers\_manbus}}$$

etc. The multipliers are listed in Table 2.14.

Table 2.14: Derived voc multipliers and vehicle operating and ownership costs (for 0.26 EUR_{2020}/vkm in PST)

Transport mode	Multipliers of costs per vkm with resepect to manual cars		Multipliers of costs per vkm with resepect to automated cars		PST/CBA initial default GDP/capita in EUR_{2020} (17,000)	
	without personnel costs	including personnel costs	without personnel costs	including personnel costs	Sum, total, per vkm	Sum total, per pkm or tkm
Car, weighted average (in PST)					***0.26***	*0.21*
Car, manual					***0.30***	*0.24*
Active travel	*0.09*	*0.09*			*0.03*	*0.03*
Bus, manual	*2.35*	*5.72*			*1.72*	*0.10*
Railed-based public transport		*27.78*			*8.33*	*0.10*
Public transport (weighted rail-road average)		*9.03*			*2.71*	*0.10*
HGV, manual	*2.15*	*5.52*			*1.66*	*0.87*
LCV, manual	*1.07*	*7.11*			*2.13*	*10.28*
Freight, manual (weighted average)	*1.18*	*6.95*			*2.09*	*5.54*
Automated car					***0.20***	*0.16*
Automated shared car (taxi)			*1.00*		*0.20*	*0.10*
Automated on-demand shuttle, 8 s. (taxi)			*2.06*		*0.41*	*0.10*
Automated on-demand shuttle, 15 s. (taxi)			*2.61*		*0.52*	*0.07*
Automated point-to-point shuttle, 10 s.			*1.19*		*0.24*	*0.05*
Automated HGV			*2.42*	*3.36*	*0.68*	*0.56*
Automated LCV			*0.97*	*3.39*	*0.68*	*5.15*
Automated freight (weighted average)			*1.12*	*3.39*	*0.68*	*2.85*
Semi-automated LCV			*1.44*	*9.69*	*1.95*	*8.24*

The figures in the two rightmost columns in

Table 2.13 and Table 2.14 only differ due to rounding errors.

The voc/vkm for freight vehicles is based directly on the figures in Table 2.11.

Cost estimates per pkm, or per tkm, are based, respectively, on the use of assumed average occupancies and average freight loads. Estimates per tkm for freight are described in the following sub-chapter and the estimates. The occupancy in passenger transport modes are presented in subchapter 2.2.2.

Freight transport cost

The PST variable *freight transport cost* – "direct outlays for transporting a tonne of goods per kilometre of travel" provides what we might consider an average weighted freight transport cost (involving all types of freight vehicles). We can assume simple relationship between freight transport cost and voc; if we apply voc with the weighted average freight loads in tonne (l_{tonne}), we have that:[35]

$$c_{\text{transport\_tkm\_freight}} = \frac{c_{\text{voc\_withpers\_vkm\_freight}}}{l_{\text{tonne\_freight}}}$$

If the freight load is exactly one tonne, there will then be a one-to-one relationship between freight costs per vkm and costs per tkm. If the load is higher, the cost for transporting a tonne of goods per kilometre of travel is lower than the (operating and ownership) cost per vkm; and *vice versa*.

Table 2.15: Default freight transport costs, EUR2020/tkm

Freight transport vehicle type	EU-28 - GDP/capita in EUR2020 (30,500)			PST/CBA initial default GDP/capita in EUR2020 (17,000)
	Vehicle operating and ownership costs (per vkm)	Freight load (tonne)	Freight transport cost (per tkm)	Freight transport cost (per tkm)
HGV, manual	*2.98*	*1.90*	*1.57*	*0.88*
LCV, manual	*3.84*	*0.21*	*18.51*	*10.32*
Freight, manual (weighted average)	*3.75*	*0.38*	*9.97*	*5.56*
Automated HGV	*1.21*	*1.20*	*1.01*	*0.56*
Automated LCV	*1.22*	*0.10*	*9.21*	*5.13*
Automated freight (weighted average)	*1.22*	*0.24*	*5.09*	*2.84*
Semi-automated LCV	*3.49*	*0.20*	*14.76*	*8.23*

Table 2.15 lists freight transport cost estimates, where the inputs and estimates for LCV build on Hu et al. (2021a, b). (Rounding errors yield slightly different numbers in the rightmost column compared to the freight vehicle estimates in the rightmost column in

[35] A parallel person transport case would involve occupancy instead of load.

Table 2.13 and Table 2.14.) The relatively low freight loads for the delivery vans (LCV) yield relatively high freight transport cost estimates (but we might presume that these loads are distance-weighted averages that also comprise driving without load). As indicated above, the HGV load is simply set to 9 times the load of the LCV. That relationship, together with the 50-50 split of the overall transport weight (tkm) beween LCV and HGV, implies that LVC takes 90% of the freight vkm against 10% for the HGV.

As the calculations in the CBA module apply vkm as unit, we apply voc/vkm for freight vehicles as well.

Taxi user costs

Sub-use cases involving ride sharing (automated passenger cars) and the use of on-demand shuttle service (automated shuttle buses) can be described as a type of automated taxi. The user cost will not be based on fixed ticket costs, as for public transport, but travel lengths, with possible price variation with respect to time of the day or other elements. Taxis without drivers will have much lower time-related ownership costs than manual taxis, thus most probably also lower user costs.

Current taxi prices in European cities may still provide a relevant tag for expected user costs for automated (shared) taxi. Based on travel magazine surveys, we find an interval per km (supposedly for individual travellers) ranging from just above 0.30 EUR in Bucharest to about 4.60 in Zurich (in 2017).[36] Including city (or country) average prices from ten countries, we estimate a population-weighted average of about 2.20 EUR/pkm. We apply 2.20 EUR_{2020} as default average taxi price per km per person, representing the EU-28 cost level of GDP/capita average of 30,500 EUR_{2020}. The default manual taxi cost ($\bar{p}_{\text{taxi\_pkm\_mancar}}$) will then be 1.23 EUR/km for the default PST/CBA GDP/capita of 17,000 EUR_{2020}.

Existing services for ride-sharing cars (or shared maxi-cabs) is supposedly cheaper per individual traveller than standard taxis or maxi-cabs (see, e.g., Frazzani et al. 2016). At the outset we set a tentative default taxi price, i) which is equal for ride sharing in automated passenger cars ($\bar{p}_{\text{taxi\_pkm\_autcar}}$) and shared use of on-demand automated shuttle service ($\bar{p}_{\text{taxi\_pkm\_autshuttle}}$); and that is simply assumed to be 50% of the weighted average found for current regular taxis; that is, 50% times 2.20 EUR_{2020} yielding 1.10 EUR_{2020}/km, at the EU-28 cost level of GDP/capita average of 30,500 EUR_{2020}. The default cost for automated shared taxi or on-demand shuttle will then be 0.61 EUR/km for the default PST/CBA GDP/capita of 17,000 EUR_{2020}.[37] Obviously, the cost for taxi users is income for the taxi (ride sharing or on demand) service provider.

Public transport tickets

The price of using public transport also varies considerably across European cities and the cost per trip will also vary with respect to the type of ticket, whether it is for a single

[36] The cost figures are due to https://www.travelandleisure.com/travel-tips/ground-transportation/carspring-taxi-index-cabs and https://www.traveldailynews.com/post/the-cheapest-and-most-expensive-taxi-fares-worldwide, both retrieved 4th of September 2021.

[37] Roussou et al. (2021a) refer to a modelling of on-demand shuttle buses where users would be charged a time-based fare of 0.30 EUR/min. That would amount to about 1 EUR/km for the travel times that we have estimated for automated shuttle buses.

trip or a season ticket. Back in 2015, the price of a single trip ticket in major European cities ranged from 1.50 Euro in Rome to 6.1 Euro in London, while the 2.70 Euro cost in Berlin probably was closer to the average in EU city areas.[38] Although the use of season tickets might yield average trip costs below this figure, for simplicity we apply 2.70 EUR_{2020} as our default single-person ticket cost per trip ($\bar{p}_{\text{public\_trip}}$), at the EU-28 cost level of GDP/capita average of 30,500 EUR_{2020}. The default cost for public transport will then be 1.50 EUR/trip for the default PST/CBA GDP/capita of 17,000 EUR_{2020}. For the sub-use cases that involve shuttle buses on fixed sections ("point-to-point"), we assume similar ticket cost for shuttle buses as for other public transport vehicles. Obviously, the cost for public transport users is income for the public transport provider.

2.2.2 Systemic impacts

Systemic impacts are described as system-wide impacts within the transport system by Elvik (2020). In the PST these comprise amount of travel (given in pkm for all transport modes except freight, but also re-calculated in vkm in the CBA module), congestion, modal split (of passenger transport), and vehicle occupancy.

Amount of travel by car, public transport, active transport, plus specific automated passenger vehicles and freight transport vehicles

PST variables for use cases involving passenger cars or shuttle buses

The PST provides total annual *amount of travel* in person kilometres (pkm), in the selected area. This sum of pkm (Q) comprises passenger cars, public transport, and active travel (cycling and walking for transport). Furthermore, the PST provides the *modal split of travel using public transport* ($s_{\text{pkm\_public}}$) and *modal split of travel using active travel* ($s_{\text{pkm\_active}}$), that are stated as percentages, such that the total amount of pkm can be distributed between the three main classes of transport modes. The default initial modal split, applied in this deliverable, is 40% public transport and 5% active transport, yielding subsequently 55% by passenger car ($s_{\text{pkm\_car}}$). For passenger transport scenarios, the CBA module applies the amount of travel, in pkm, and the modal shares from the PST.

Specific input about trip distances of shuttle buses and ride-sharing taxis

In the case of the automated urban shuttle service (AUSS), their pkm will be included in the *modal split of travel using public transport* ($s_{\text{pkm\_public}}$). The specific share of AUSS in public transport is not available from the PST though; but the CBA module will insert AUSS vkm and other shuttle-bus input from the underlying simulations and documentations (Roussou et al. 2021a, b; see section 2.4.4). The amount of travel, from the PST, can be applied for scaling the absolute size of the AUSS. As indicated, automated shuttle buses will only enter PST/CBA when AUSS sub-use cases (policy scenarios).

[38] The 2015 cost figures are due to https://www.statista.com/statistics/605574/public-transport-ticket-price-europe-city/, retrieved 28th of June 2021. The European average public transport ticket price in 2019 was 2.74 Euro, according to https://www.kiwi.com/stories/cheapest-and-most-expensive-public-transport-revealed/, retrieved 28th of June 2021.

Automated ride sharing, will be included in the pkm share of passenger car transport ($s_{\text{pkm\_car}}$), when this sub-use case is implemented. The sub-use case resembles closely the on-demand AUSS. The specific share of automated ride-sharing is not available from the PST though; but the CBA module will insert automated ride-sharing vkm and other relevant input from the underlying simulations and documentations (Haouari et al. 2021; see section 2.4.4). The amount of travel, from the PST, can be applied for scaling the absolute size of the automated ride-sharing vkm, etc.

Specific input about trip distances of freight transport

Freight transport scenarios in the PST do not convey information about transport distances. The CBA module will insert vkm and other relevant input, regarding the selected type of freight vehicles in baseline and policy, from the underlying simulations and documentations (Hu et al. 2021a, b; see section 2.4.4).

The freight vehicles in the selected sub-use case will only comprise part of the freight transport in the PST area. The other freight transport, beyond the sub-use case, can be derived from the given (assumed) relationship between sub-use case freight and the other freight, say 1 to 9 in terms of total freight vkm (section 2.4.4). While the freight vehicle type is specified in the freight sub-use case, fixed shares of LCV and HGV can be set for the other freight, say 90% LCV and 10% HGV in terms of the vkm.

In the freight transport scenarios, the crash risk and the emissions per vkm will also comprise passenger transport vehicles (see section 2.2.3). As costs levels will differ between transport modes, the CBA module also invokes passenger transport based on total freight vkm. It requires an estimate of the relative shares of freight transport vkm vs. passenger transport vkm, say 10% freight and 90% passenger transport.

As the emissions per vkm under passenger transport scenarios also will comprise emissions from freight transport scenarios, the CBA module also invokes freight transport under passenger transport scenarios. The same estimate of relative vkm shares apply. It brings freight transport scenarios and passenger transport scenarios into a common overall frame with the same set of transport modes; although the focus and pattern of change will differ considerably between freight and passenger transport scenarios.

Summarising use case and sub-use case specific transport modes

For the sub-use cases involving freight transport as well as passenger transport involving AUSS and automated ride sharing, the PST provides no separate input on transport distances for these vehicles. We apply specific input for the CBA module (section 2.4.4). These sub-use cases will introduce the following additional classes or sub-classes of transport modes:

- sub-use case freight vehicles – manual, semi-automated, and automated LCV, as well as manual and automated HGV;
- other (non-sub-use case) freight vehicles – the shares of automated LCV and automated HGV are determined by MPR for freight (Table 2.1);
- automated point-to-point shuttle buses (10 seats capacity) – users are assumed to pay with ordinary public transport tickets (per trip);
- automated on-demand shuttle buses (8 or 15 seats capacity) – users are assumed to pay per pkm, as a type of taxi; and
- automated ride-sharing passenger cars – users are assumed to pay per pkm, as a type of taxi.

In the CBA module, we include these specific transport modes in a unified setting for all transport modes. The unified approach in the CBA will facilitate the handling of some aggregated PST input, primarily related to emission costs, to some extent also crash costs and congestion costs. E.g., the calculation/allocation of internal and external costs for each transport mode will show how the particular mode is affected by the sub-use cases in terms of internal cost changes and consumer surplus changes, as well as how their role in "producing" external effects is affected.

PST variables for use cases involving freight vehicles

As indicated, the PST will not provide transport distances under freight transport scenarios, neither for freight nor other transport. The invoking of vkm in the CBA module under freight transport scenarios has three steps (see also section 2.4.4):

i) Firstly, the vkm of the specific freight element in the sub-use case (SUC-freight, $T_{\text{freightSUC}}$) is set based on Hu et al. (2021a, b) and the vkm in underlying simulations of the PST demo-spreadsheets for the freight sub-use cases; and these are scaled with the PST variable *city population* (with 2 million as original scale).

ii) Secondly, the vkm of the non-sub-use case freight is set to nine times the baseline SUC-freight vkm for manual LCV delivery ($T_{\text{freightNONSUC}} = T_{\text{freightSUC\_manLCV}} * 9$), as default; this yields total freight vkm ($T_{\text{freight}} = T_{\text{freightSUC}} + T_{\text{freightNONSUC}}$); the non-SUC freight has 90% vkm by LCV and 10% vkm by HGV, as default.

iii) Thirdly, the vkm of passenger transport is set to nine times the freight transport vkm ($T_{\text{passenger}} = T_{\text{freight}} * 9$), as default.

The second step follows from the assumed 10% default share of the SUC-freight baseline in overall freight transport vkm. That is:

$$\frac{T_{\text{freightSUC\_manLCV}}}{T_{\text{freightSUC\_manLCV}} + T_{\text{freightNONSUC}}} = 0.1 \quad \xrightarrow{yields} \quad T_{\text{freightNONSUC}} = T_{\text{freightSUC\_manLCV}} * 9$$

The non-SUC freight transport vkm is then 9 times the baseline SUC-freight for manual delivery; and $T_{\text{freight}} = T_{\text{freightSUC}} + T_{\text{freightNONSUC}}$. So, total freight vkm, might vary slightly between freight SUC cases that have slightly varying annual vkm, as $T_{\text{freightSUC}}$ is not necessarily equal to $T_{\text{freightSUC\_manLCV}}$.

Similarly, the third step follows from the assumed 10% default share of freight in overall transport vkm. That is:

$$\frac{T_{\text{freight}}}{T_{\text{freight}} + T_{\text{passenger}}} = 0.1 \quad \xrightarrow{yields} \quad T_{\text{passenger}} = T^{*}_{\text{freight}} * 9$$

where $T^{*}_{\text{freight}} = T_{\text{freightNONSUC}} + T_{\text{freightSUC\_manLCV}}$, which ensures that passenger transport vkm does not fluctuate with SUC-freight vkm. The passenger transport vkm is 9 times the baseline level of freight transport vkm.

The invoking of all freight vkm and passenger vkm, in the selected PST area, is based on the common transport mode-based framework of the PST. Obviously, freight transport scenarios will primarily affect the specific freight element in the sub-use case (SUC-freight, $T_{\text{freightSUC}}$). However, some freight PST inputs will relate indirectly to the remaining freight activity and the passenger transport, particularly the level of congestion and the safety/crash level. These impacts are attributed to different transport modes (as specified in section 2.2.3). Moreover, the common approach across scenarios establishes a common CBA module for all types of LEVITATE scenarios.

Applying default modal shares for passenger transport (from passenger car / shuttle bus PST) and their occupancies, we can derive the modal shares of passenger transport vkm as well. Then we can derive all the calculations that relate to congestion costs, crash costs, and any other costs per transport mode.

For freight transport in general, beyond the focus of the freight sub-use cases, we apply defaults of 90% of all freight vkm by LCV ($s_{\text{vkm\_LCV}} = 0.9$), leaving 10% of the freight vkm by HGV ($s_{\text{vkm\_HGV}} = 1 - s_{\text{vkm\_LCV}} = 0.1$), when simplifying to only two freight vehicle classes. The relative freight load has a default of 9 to 1, for HGV against LCV ($l_{\text{tonne\_HGV}} = l_{\text{tonne\_LCV}} * 9$). That implies equal shares (50%-50%) of tkm for LCV and HGV ($s_{\text{tkm\_HGV}} = 1 - s_{\text{tkm\_LCV}} = 0.5$).

Vehicle occupancy

<u>LEVITATE assumptions for cars and shuttles plus assumptions for public transport</u>

The *vehicle occupancy rate* (the percentage of vehicle capacity used), or the number of passengers per vehicle, is important in terms of the potential impacts of the policy scenarios. The occupancy is also particularly useful in the CBA, enabling calculations back and forth between estimates per pkm and estimates per vkm.

The PST default for the vehicle occupancy rate, for passenger cars, is 25%, implying 1.25 persons per car on average ($n_{\text{occ\_car}} = 1.25$).[39] One of the policy scenarios is automated ride sharing in passenger cars (taxi). For the application related to that sub-use case, it will be assumed that the average number of passengers is two ($n_{\text{occ\_taxi\_car}} = 2$). Automated shuttle buses, within LEVITATE, are assumed to consist of three types: one with 10 seats for point-to-point public transport, and for on-demand taxi one smaller type with eight seats and a larger one with 15 seats. An average occupancy rate of 50% is applied, yielding $n_{\text{occ\_autshuttle8}} = 4$, $n_{\text{occ\_autshuttle10}} = 5$, and $n_{\text{occ\_autshuttle15}} = 7.5$ (Roussou et al. 2021a).

Public transport consists of many types of modes with different capacities. Rail-based transport will not be directly impacted by LEVITATE policy scenarios, but as public transport can be affected, e.g., via changes in modal share, also the use of rail-based transport might be affected indirectly. For metro and other heavy rail (suburban, regional, national), we have assumed three wagons as an average, multiplied by the average passenger capacity per wagon (vehicle) in Jagiełło et al. (2018). The occupancy

[39] Elvik (2020) proposed 1.5 persons per car on average, for manual and automated cars alike. For a five-seat car, that would imply an occupancy rate of 30%. The implied occupancy in van Essen et al. (2019) is 1.6, but they refer to 1.7 for the whole EU area, which is also applied by Fioriello et al. (2016). However, the occupancy rate of cars is relatively lower in the more urban areas (EEA 2020). A general feature regarding automated private cars is that they will enable empty driving. Automated car owners, when going somewhere for some activity, might prefer to send their car back (home or elsewhere) empty, instead of leaving the car in a parking lot. Then, after the activity, the owner might call for the car, which will run empty, e.g., from the garage at the residence to the location where the owner wants the car to pick him/her up. That might yield an average occupancy for the automated vehicle which is below 1; the pkm total will be less than the vkm total. However, the CBA can transpose valuations between pkm and vkm, using the occupancy. It doesn't matter, in terms of CBA functionality, whether the (average) occupancy is 1.25 or 0.75.

rate is set somewhat arbitrarily to 30% of capacity. This would imply that slightly less than half the seats are occupied, which is within presented intervals of 28-62% (EEA 2020, ECA 2014). The estimated passenger numbers in buses and trains are almost equal to those applied by van Essen et al. (2019). The shares of urban public transport modes are due to UITP (2016).[40] The vkm-weighted mean occupancy for all urban public transport is 28, $n_{\text{occ\_public}} = 28$ (**Error! Reference source not found.**). This is a weighted average of bus (including trolley/BRT), with an average occupancy of $n_{\text{occ\_bus}} = 18$, and the various rail-based modes, with an average weighted occupancy of $n_{\text{occ\_rail}} = 85$.

Occupancy as a link between pkm and vkm

Table 2.16 summarises our assumptions about occupancy, also including default travel distance in the PST, in pkm and vkm; the vkm is derived from total pkm, modal shares, and occupancies. The freight transport is added as a 10% share of all transport.

Table 2.16: Default occupancies, shares of pkm, and shares of vkm - passenger transport scenarios

Transport mode	Pass-enger capacity	Occup-ancy rate	Occu-pancy	Share pkm		vkm if pkm= 100	Share vkm		Weighted occu-pancy
Active transport	1	100%	1	*5,0%*	*5%*	*5,00*	*9,91%*	*9,91%*	1
Manual cars	5	25%	1,25	*22,0%*	*55%*	*17,60*	*34,89%*	*87,23%*	1,25
Aut. cars, 1st gen.	5	25%	1,25	*22,0%*		*17,60*	*34,89%*		
Aut. cars, 2nd gen.	5	25%	1,25	*11,0%*		*8,80*	*17,45%*		
Aut. ride-share taxi	5	40%	*2*	*0,0%*		*0,00*	*0,00%*		
Aut. shuttle	8	50%	*4*	*0,0%*	*40%*	*0,00*	*0,00%*	*2,86%*	*28*
Aut. shuttle	15	50%	*7,5*	*0,0%*		*0,00*	*0,00%*		
Aut. shuttle	10	50%	*5*	*0,0%*		*0,00*	*0,00%*		
Bus	*60*	*30%*	*18*	*22,0%*		*1,22*	*2,42%*		
Metro	*350*	*30%*	*105*	*6,0%*		*0,06*	*0,12%*		
Tram	*200*	*30%*	*60*	*6,0%*		*0,10*	*0,20%*		
Other (heavy) rail	*350*	*30%*	*105*	*6,0%*		*0,06*	*0,12%*		
All pass. transport				*100%*	*100%*	*50,44*	*100%*	*100%*	*2,0*
Added freight, vkm						*5,60*			
LCV, vkm						*5,04*	*90%*		
HGV, vkm						*0,56*	*10%*		

[40] A 1% share of BRT (trolleys) ridership in the pkm share of buses can be estimated from relative share of BRT ridership in Ellis (2015) versus tram ridership in UITP (2019) and the tram share in UITP (2016). The occupancy numbers for bus and rail applied by van Essen et al. (2019) are 19 and 104 (and 173 for high-speed trains), comprising transport in the whole EU. The relative shares of rail-based urban transport and bus/trolley transport, that we apply, are also very close to figures for all passenger transport in EU (Eurostat 2020).

Sources: The shares of public transport types are based on Jagiełło et al. (2018, Table 1, orig. source Wyszomirski 2010); UITP (2016, Figure 1); EEA (2020); UITP (2019); and Ellis (2015). We apply rounded figures, slightly downscaling bus (incl. shuttles) and metro while slightly upscaling tram (incl. light rail) and sub-urban/regional/national (heavy) rail; that is, the pkm-weighted public transport comprises 15% of each of the three rail-based types and 55% bus.

The invoking of non-SUC freight vkm and passenger transport vkm, as depicted in **Error! Not a valid bookmark self-reference.**, will be based solely on a common baseline SUC freight vkm (manual delivery by LCV, $T_{\mathrm{freightSUC\_manLCV}}$); thus non-SUC freight vkm and passenger transport vkm will not differ between baseline and policy scenario.

Comparing Table 2.16 and Error! Not a valid bookmark self-reference., for common assumptions about pkm, occupancy, and vkm distributions in passenger transport the vkm transport distances between passenger and freight transport scenarios, within the same PST area, only differ due to rounding errors.

An implicit vkm-based modal split for passenger transport can be derived from either the pkm-based estimates and occupancies (in passenger transport scenarios) or derived from total passenger transport vkm (in freight transport scenarios) with pkm-modal split and occupancy.

Table 2.17. provides a similar set-up for freight transport scenarios. In that case, the passenger transport is added as a 90% share of all transport.

The invoking of non-SUC freight vkm and passenger transport vkm, as depicted in **Error! Not a valid bookmark self-reference.**, will be based solely on a common baseline SUC freight vkm (manual delivery by LCV, $T_{\mathrm{freightSUC\_manLCV}}$); thus non-SUC freight vkm and passenger transport vkm will not differ between baseline and policy scenario.

Comparing Table 2.16 and **Error! Not a valid bookmark self-reference.**, for common assumptions about pkm, occupancy, and vkm distributions in passenger transport the vkm transport distances between passenger and freight transport scenarios, within the same PST area, only differ due to rounding errors.

An implicit vkm-based modal split for passenger transport can be derived from either the pkm-based estimates and occupancies (in passenger transport scenarios) or derived from total passenger transport vkm (in freight transport scenarios) with pkm-modal split and occupancy.

Table 2.17: Derived shares of vkm, and shares of pkm - freight transport scenarios

Transport mode	Share vkm	vkm	Occu-pancy	Weighted occu-pancy	pkm if vkm-pass.tr. =50,4	Share pkm
SUC - freight, vkm	*10%*	***0,56***				
Other freight, vkm	*90%*	*5,04*				
LCV (other), vkm	*90%*	*4,54*				
HGV (other), vkm	*10%*	*0,50*				

All freight transport, vkm			5,60					
Added passenger transport, vkm			50,40					
Active transport	9,91%	9,91%	4,99			5,0	5,0%	5,0%
Manual cars	34,89%	87,23%	17,58	1,25	1,25	22,0	21,9%	54,7%
Aut. cars, 1st gen.	34,89%		17,58	1,25		22,0	21,9%	
Aut. cars, 2nd gen.	17,45%		8,79	1,25		11,0	10,9%	
Aut. ride-share taxi	0,00%		0,00	2		0,0	0,0%	
Aut. shuttle, 8 seats	0,00%	2,86%	0,00	4	28	0,0	0,0%	40,5%
Aut. shuttle, 15 seats	0,00%		0,00	7,5		0,0	0,0%	
Aut. shuttle, 10 seats	0,00%		0,00	5		0,0	0,0%	
Bus	2,42%		1,22	18		22,0	21,9%	
Metro	0,12%		0,06	105		6,3	6,3%	
Tram	0,20%		0,10	60		6,0	6,0%	
Other (heavy) rail	0,12%		0,06	105		6,3	6,3%	

If we have a passenger transport scenario in PST, we have: total pkm (Q), and we have the modal shares of public transport ($s_{\text{pkm\_public}}$), active transport ($s_{\text{pkm\_active}}$), and, implicitly, the residual share of passenger cars ($s_{\text{pkm\_car}}$). That yields the pkm for each of these main passenger modes ($Q_{\text{public}}=s_{\text{pkm\_public}} * Q$; $Q_{\text{active}}=s_{\text{pkm\_active}} * Q$; and $Q_{\text{car}}=s_{\text{pkm\_car}} * Q$).[41]

Applying occupancies, we have that, e.g., vkm for manual passenger cars is given by: $T_{\text{mancar}} = Q_{\text{mancarc}}/n_{\text{occ\_mancar}}$; and equivalently for the other passenger transport modes. The vkm share of each transport mode can be derived, e.g., for automated cars, as: $s_{\text{vkm\_autcar}} = T_{\text{autcar}}/T_{\text{passenger}}$, where $T_{\text{passenger}}$ is the sum of passenger transport vkm ($T_{\text{passenger}} = T_{\text{public}} + T_{\text{active}} + T_{\text{car}}$).

When AUSS sub-use cases are implemented, their vkm is calculated as part of the public transport vkm: $T_{\text{public}} = T_{\text{rail}} + T_{\text{bus}} + T_{\text{autshuttle}}$; the AUSS pkm is part of the public

[41] Obviously, the pkm for different types of cars, the manual and the autonomous 1st and 2nd generation, is derived from the MPR for passenger cars; that is: $s_{\text{pkm\_car}}=s_{\text{pkm\_mancar}} + s_{\text{pkm\_aut1car}} + s_{\text{pkm\_aut2car}}$; and $Q_{\text{car}}=Q_{\text{mancar}} + Q_{\text{aut1car}} + Q_{\text{aut2car}}$.

transport pkm, in the PST. When automated ride-sharing cars are implemented, their vkm is calculated as part of the passenger cars: $T_{\text{car}} = T_{\text{mancar}} + T_{\text{autcar}} + T_{\text{autcartaxi}}$.[42]

The share of public transport vkm is much smaller than the public transport pkm. If the pkm modal shares are 40%, 5%, and 55%, respectively for public transport, active transport, and car, then if occupancies are 28, 1, and 1.25, the vkm modal shares will be 2.86% of total vkm by public transport, 9.91% by active transport, and 87.23% by car.

We add freight transport vkm in passenger transport scenarios, primarily to allocate emissions and congestion to the full set of transport modes, If freight transport, T_{freight}, is 10% of total vkm, then total vkm (passenger transport plus freight transport) is:

$$T = T_{\text{passenger}} + \left(\frac{1}{9} * T_{\text{passenger}}\right) = T_{\text{passenger}} + T_{\text{freight}}$$

If we have a freight transport scenario in PST, then we have $T_{\text{freightSUC\_manLCV}}$ as the baseline SUC-freight vkm at the outset. The other freight is:

$$T_{\text{freightNONSUC}} = T_{\text{freightSUC\_manLCV}} * 9$$

and

$$T_{\text{freight}} = T_{\text{freightNONSUC}} + T_{\text{freightSUC}}$$

(where the SUC-freight vkm might be equal to manual LCV delivery vkm, but not necessarily, see section 2.4.4). The passenger transport is:

$$T_{\text{passenger}} = T^{*}_{\text{freight}} * 9$$

where $T^{*}_{\text{freight}} = T_{\text{freightNONSUC}} + T_{\text{freightSUC\_manLCV}}$, ensuring that passenger transport vkm does not fluctuate artificially with SUC-freight vkm between baseline and policy (as $T_{\text{freightSUC}}$ might vary, and subsequently also T_{freight}, but not $T_{\text{freightNONSUC}}$ and T^{*}_{freight}, thus not $T_{\text{passenger}}$ either). All details about passenger transport modes can be retrieved by the default pkm shares, occupancies, and subsequent vkm shares. The vkm shares (not pkm shares) are applied when distributing passenger transport vkm across passenger transport modes under freight transport scenarios.

Congestion

The PST variable – seconds of delay per vkm

In the PST, *congestion* is measured as average delays to traffic, in seconds per vehicle-kilometre (as a result of high traffic volume), $d_{\text{sec\_km}}$. It is congestion created by all types of motorised transport modes on the road within the given geographical area. This variable is defined in the same way, in the PST, whether the focus is on passenger cars, shuttle buses, or freight vehicles. As already indicated, we assume that this average delay applies equally to passenger cars and freight vehicles, that is, the weighted averages of manual and automated vehicles ($d_{\text{sec\_km\_car}} = d_{\text{sec\_km\_freight}} = d_{\text{sec\_km}}$).[43]

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[42] Obviously, when freight-transport sub-use cases are implemented, their vkm is calculated as part of total freight vkm: $T_{\text{freight}} = T_{\text{freightNONSUC}} + T_{\text{freightSUC}}$.

[43] In one passenger car sub-use case, involving road-use pricing (static toll and dynamic toll), delay, congestion, is not included. In that case we apply a default constant average delay/vkm of 200 sec.

We assume that the delay affects 25% of pkm and tkm ($k_{\text{pkm\_cong}} = k_{\text{tkm\_cong}} = 0.25$). Moreover, we assume that automated vehicles are 17% less affected by delay, in terms of travel time reduction during congestion, compared to manual vehicles. As indicated under the section about travel time ($h_{\text{min\_km}}$), under congestion we have that, e.g.:

$$h_{\text{min\_km\_cong\_mancar}} = \frac{h_{\text{min\_km\_cong\_car}}}{s_{\text{mancar}} + s_{\text{autcar}} - (s_{\text{autcar}} * 0.17)}$$

and

$$h_{\text{min\_km\_cong\_autcar}} = h_{\text{min\_km\_cong\_mancar}} - \left(h_{\text{min\_km\_cong\_mancar}} * 0.17\right)$$

and equivalently for the relationship between manual and automated freight vehicles.

For the valuation of delay, estimating internal congestion costs, in the CBA we apply the PST delay variable in combination with the valuation of time savings in passenger transport and operating/ownership costs in freight transport.

The internal congestion costs

We have shown in the tables above (from Table 2.4 to

Table 2.7, as well as in Table 2.10) that VTTS under congestion is higher than VTTS under free-flow. The share of all passenger travel under congestion can thus be allocated a higher VTTS, reflecting an internal congestion cost for the individual traveller (Table 2.10). E.g.:

$$w_{\text{hour\_manbus\_cong}} = w_{\text{hour\_manbus\_flow}} * \omega_{\text{cong}}$$

and we propose a default VTTS congestion multiplier (ω_{cong}) of 1.42 (based on Wardman et al. 2016). As already indicated, we disregard congestion in rail-based transport and in active transport.

We have shown that the share of travel time in congestion ($k_{\text{traveltime\_cong}}$) is higher than than the share of vkm in congestion ($k_{\text{vkm\_cong}} = 0.25$). E.g.:

$$k_{\text{traveltime\_cong\_car}} = \frac{k_{\text{vkm\_cong\_car}} * h_{\text{min\_km\_cong\_car}}}{(k_{\text{vkm\_flow\_car}} * h_{\text{min\_km\_flow\_car}}) + (k_{\text{vkm\_cong\_car}} * h_{\text{min\_km\_cong\_car}})}$$

Based on the applied PST default inputs, we obtain slightly less than a 50% share of travel time in congestion for cars and freight vehicles; it is lower, below 40%, for public transport (due to the share of rail-based transport).

In the CBA, congestion costs per vkm will be estimated for all included transport modes. For passenger transport, we then have, for internal congestion costs ($c_{\text{int\_cong\_vkm}}$), e.g.:

$$c_{\text{int\_cong\_vkm\_mancar}} = w_{\text{vkm\_mancar\_cong}} - w_{\text{vkm\_mancar\_flow}}$$

etc. That is, the internal congestion cost per vkm for passenger transport is equal to the transport mode user's additional valuation of travel time savings per km in congestion relative to the valuation of travel time savings under free-flow conditions.

Table 2.18: Deriving internal congestion costs, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

Transport mode	Additional VTTS per hour in congestion	Travel time, hours per km, under congestion	Occupancy	Additional VTTS per vkm in congestion / personnel costs per vkm in freight voc
Active transport	*€0.00*	*0.1000*	*1*	*€0*
Car, manual	*€3.80*	*0.0980*	*1.25*	*€0.47*
Car, automated, 1st gen.	*€2.47*	*0.0820*	*1.25*	*€0.25*
Car, automated, 2nd gen.	*€2.47*	*0.0820*	*1.25*	*€0.25*
Shuttle bus, 8 seats, automated	*€1.89*	*0.1053*	*4*	*€0.80*
Shuttle bus, 10 seats, automated	*€1.89*	*0.1053*	*5*	*€1.00*
Shuttle bus, 15 seats, automated	*€1.89*	*0.1053*	*7.5*	*€1.49*
Public transport	*€1.89*	*0.0952*	*28*	*€5.04*
HGV, manual		*0.1020*		*€1.82*
LCV, manual		*0.1020*		*€3.03*
Freight, manual (weighted average of HGV & LCV)		*0.1020*		*€2.91*
HGV, automated		*0.0847*		*€0.48*

LCV, automated	*0.0847*	*€0.80*
Freight, automated (weighted average of HGV & LCV)	*0.0847*	*€0.77*

Setting an internal congestion cost for freight will to a large extent depend on the type of freight.[44] However, we might consider time-related ownership costs, that primarily reflect personnel costs, thus:

$$c_{\text{int\_cong\_vkm\_freight}} = c_{\text{voc\_withpers\_vkm\_freight}} - c_{\text{voc\_nopers\_vkm\_freight}}$$

This internal congestion cost for freight (applying to the share of travel time in congestion) can be set as fixed shares of the voc/vkm:

$$c_{\text{int\_cong\_vkm\_freight}} = \omega_{\text{int\_cong\_vkm\_freight}} * c_{\text{voc\_withpers\_vkm\_freight}}$$

The multiplier ($\omega_{\text{int\_cong\_vkm\_freight}}$) will be higher for manual than for automated, and higher for LCV than for HGV. For manual LCV the congestion cost share of voc/vkm is 85%, while it is 61% for manual HGV. For automated freight vehicles the shares are 71% and 28%, respectively for LCV and HGV; the weighted averages are 83% for manual and 67% for automated freight vehicles.[45]

Table 2.18 shows the derived internal congestion costs per vkm. For passenger transport we apply the VTTS difference in congestion versus free flow, the estimated travel time under congestion, and the occupancy. For freight transport we apply the personnel costs per vkm, from the vehicle operating costs.

The calculations across transport modes will enter infrastructure users' internal costs.

<u>The external congestion costs</u>
Van Essen et al. (2019) present estimates of the external cost of congestion, the "social congestion cost"; based on the deadweight loss under different levels of congestion, on different road infrastructure.[46] We include only costs occurring under congestion in urban areas; and as van Essen et al. (2019) only provide estimates on inter-urban roads for other vehicles than passenger cars, we combine the estimate for passenger cars (in their Table 46) with their estimates of generated costs in urban traffic for all transport modes (in their Table 43). Estimating congestion costs for manual (non-automated) shuttle buses as a point-of-departure, we propose an average of the estimates for cars and for

[44] The average Dutch valuation of freight time savings in 2004, reported by de Jong (2007): 4.70 EUR/hour; the GDP level in the Netherlands in the beginning of the millennium was about equal to the level for EU-28 in 2020. However, the internal congestion cost for freight transport comprises more than increased personell costs. The valuation of freight transport reliability will vary considerably with respect to the type of goods transported. De Jong et al. (2014) reported an average valuation of road freight reliability of 34 EUR/hour per vehicle (non-container freight on 2-15t trucks). A GDP-based transformation from Dutch levels in 2010 would yield an estimate just below 30 EUR for EU-28 in 2020.

[45] For the given PST vehicle operation (and ownership) cost, assumption of automation levels (MPR scenario), as wll as the assumed multiplicators (**Error! Reference source not found.**), we estimated 2.91 EUR_{2020}/vkm in time-related costs (personnel costs) for the average manual freight vehicle and 0.77 EUR_{2020}/vkm for the average automated freight vehicle.

[46] The (external) deadweight loss refers to a loss in economic efficiency; it is related to the problem of wrong/lacking pricing, as the individuals do not face the full cost of congestion when they themselves enter the traffic (van Essen et al. 2019, p. 103-105).

"large" buses. Somewhat similarly for freight, we estimate congestion costs for an average manual freight vehicle, a weighted average of the two specified freight categories, HGV and LCV.

Table 2.19 shows the estimates of external congestion costs per vehicle kilometre ($c_{\text{ext\_cong\_vkm}}$), GDP-updated from EUR_{2016} to EUR_{2020} (30,500/29,310), with our own derived estimates in italics.

The estimated differences between the manual transport modes are close to what van Essen et al. (2019, p. 112) term their "passenger car equivalent", which is "equal to: 1 for cars, 2 for HGVs and bus/coaches, 1.5 for LCVs".

We have assumed zero social congestion costs for rail-based (and active) transport. Public transport is a vkm-weighted average of bus transport (85%) and rail-based transport (15%). As indicated in our sub-section on travel time, Elvik et al. (2020) reviewed the literature on delay-reducing effect (related to improved road capacity exploitation) of automated vehicles, finding a maximum of 17% (in full automation). We have assumed linearity and have set the social congestion cost 17% lower for all types of automated vehicles.

Table 2.19: Social congestion costs in congested urban traffic, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

Transport mode	**Socical costs per vkm**		
	Urban arterial	**Other urban road**	**All urban roads (simple average)**
Active transport	*0*	*0*	*0*
Car, manual	0.26	0.61	*0.43*
Car, automated	0.21	0.50	*0.36*
Bus/coach (manual)	*0.51*	*1.19*	*0.85*
Rail-based	*0*	*0*	*0*
Public transport	*0.43*	*1.01*	*0.72*
Shuttle bus, manual (simple average of car & bus)	*0.33*	*0.77*	*0.55*
Shuttle bus, automated	*0.27*	*0.64*	*0.45*
HGV (manual)	*0.50*	*1.17*	*0.84*
LCV (manual)	*0.39*	*0.92*	*0.65*
Freight, manual (weighted average of HGV & LCV)	*0.40*	*0.94*	*0.67*
HGV, automated	*0.41*	*0.97*	*0.69*
LCV, automated	*0.32*	*0.76*	*0.54*
Freight, automated (weighted average of HGV & LCV)	*0.33*	*0.78*	*0.56*

Source: van Essen et al. (2019, Tables 43, 46).

In the CBA module, the external congestion costs per vkm will be fixed for each transport mode; they are given from The estimated differences between the manual transport modes are close to what van Essen et al. (2019, p. 112) term their "passenger car equivalent", which is "equal to: 1 for cars, 2 for HGVs and bus/coaches, 1.5 for LCVs".

We have assumed zero social congestion costs for rail-based (and active) transport. Public transport is a vkm-weighted average of bus transport (85%) and rail-based transport (15%). As indicated in our sub-section on travel time, Elvik et al. (2020) reviewed the literature on delay-reducing effect (related to improved road capacity exploitation) of automated vehicles, finding a maximum of 17% (in full automation). We have assumed linearity and have set the social congestion cost 17% lower for all types of automated vehicles.

Table 2.19 combined with our assumption of a fixed 25% of vkm (and pkm and tkm) occurring under congestion. That is, we add the assumption that average freight quantities and average occupancies are the same under congestion and free flow, such that $k_{\mathrm{vkm\_cong}} = k_{\mathrm{pkm\_cong}} = k_{\mathrm{tkm\_cong}} = 0.25$. The social costs, the deadweight loss, will affect other infrastructure users but also impact on society in wider terms. So, the external congestion costs will enter society's external costs (M_{external}).

<u>Summarising the internal and external congestion costs per vkm</u>

Table 2.20 summarises the estimated default internal and external social congestion costs, from Table 2.18 and The estimated differences between the manual transport modes are close to what van Essen et al. (2019, p. 112) term their "passenger car equivalent", which is "equal to: 1 for cars, 2 for HGVs and bus/coaches, 1.5 for LCVs".

We have assumed zero social congestion costs for rail-based (and active) transport. Public transport is a vkm-weighted average of bus transport (85%) and rail-based transport (15%). As indicated in our sub-section on travel time, Elvik et al. (2020) reviewed the literature on delay-reducing effect (related to improved road capacity exploitation) of automated vehicles, finding a maximum of 17% (in full automation). We have assumed linearity and have set the social congestion cost 17% lower for all types of automated vehicles.

Table 2.19.

Table 2.20: Deriving external congestion costs, applying transport distance under congestion (vkm) and social congestion costs per vkm

Transport mode	EU-28 - GDP/capita in EUR_{2020} (*30,500*)		PST/CBA initial default GDP/capita in EUR_{2020} (17,000)	
	Internal congestion costs per vkm	**External congestion costs per vkm**	**Internal congestion costs per vkm**	**External congestion costs per vkm**
Active transport	*0*	*0*	*0*	*0*
Car, manual	*0.47*	*0.43*	*0.26*	*0.24*
Car, autom., 1st gen.	*0.25*	*0.36*	*0.14*	*0.20*
Car, autom., 2nd gen.	*0.25*	*0.36*	*0.14*	*0.20*
Shuttle bus, 8 seats	*0.80*	*0.45*	*0.45*	*0.25*
Shuttle bus, 10 seats	*1.00*	*0.45*	*0.56*	*0.25*
Shuttle bus, 15 seats	*1.49*	*0.45*	*0.83*	*0.25*
Public transport	*5.04*	*0.72*	*2.81*	*0.40*
LCV (manual)	*1.82*	*0.84*	*1.01*	*0.47*
HGV (manual)	*3.03*	*0.65*	*1.69*	*0.36*
Freight, manual (weighted average)	*2.91*	*0.67*	*1.62*	*0.37*
LCV, automated	*0.48*	*0.69*	*0.27*	*0.38*
HGV, automated	*0.80*	*0.54*	*0.45*	*0.30*
Freight, automated (weighted average)	*0.77*	*0.56*	*0.43*	*0.31*

For the given delay and travel times, that affects internal delay costs, the estimated internal and external congestion costs are mostly within the same order of magnitude.

2.2.3 Wider impacts

Wider impacts are described by Elvik (2020) as changes that are occurring outside the transport system. However, the wider impacts in the PST represent a mix of impacts within and beyond the transport system. The impacts defined as "wider" comprise road safety (no. of crashes in the road infrastructure), emissions of (local) air pollutants and greenhouse gases, as well as required parking space and commuting distances.

Road safety – crash rates involving partly varying subsets of road users across scenarios

The handling of the crash number variable

In the PST, *road safety total effect* ("road safety effects when accounting for VRU and modal split") is measured as number of crashes per million vkm. The crashes comprise all levels of injury severity, also including crashes that result only in material damage. This PST variable (RSTE, or $n_{\mathrm{crash\_Mvkm}}$) will comprise all crashes between passenger cars (RSM) as well as (injury) crashes between passenger cars and cyclists/pedestrians

(VRU).[47] This content of the PST variable applies to all types of passenger transport scenarios, whether the focus is on passenger cars or automated urban shuttle buses, as well as on freight transport scenarios. For scenarios involving freight, the PST variable will also comprise crashes involving freight vehicles (collisions between freight vehicles, between freight vehicles and cars, between cars, injury crashes between freight vehicles and cyclists/pedestrians, and injury crashes between cars and cyclists/pedestrians).

Crashes involving public transport vehicles, beyond automated shuttle buses, are omitted in all types of scenarios.[48] Crashes involving shuttle buses are included in the policy scenarios under the automated urban transport service (AUSS) sub-use cases.

<u>The average crash cost</u>

The crash rate can be monetised by use of some weighted average of injury severity and valuations per crash. The following table shows such an estimated weighted average based on Wijnen et al. (2017); and we assume that the original values are EUR_{2016}.

Table 2.21: Weighted average cost of a crash (adjusted for under-reporting)

Maximum injury level in crash	**Cost per crash (EUR_{2016}), GDP/capita EUR_{2016} 29,310**	**Share**	**Cost per crash times share, updated to EUR_{2020}**	
			EU-28 - GDP/capita in EUR_{2020} (*30,500*)	**PST/CBA initial default GDP/capita in EUR_{2020} (17,000)**
Fatality	2,300,000	0.1%	*2393*	*1334*
Serious/severe injury	300,000	1.4%	*4371*	*2436*
Slight injury	23,000	21.7%	*5194*	*2895*
Property damage only	3500	76.8%	*2797*	*1559*
Weighted average	14,179	100%	*14,755*	*8224*
Rounded average			*14,800*	*8250*

Source: Wijnen et al. (2017, p.75 & table 6.6, p.72).

[47] For freight transport scenarios we lack the PST variable, *road safety total effect* (RSTE). However, the PST also includes *road safety motorised*, "the no. of (motorised) crashes per mill. vehicle-kilometre driven" (RSM). $\mathrm{RSTE} = \Big(\big(\mathrm{RSM} * Q * (1 - s_{\mathrm{pkm\_public}} - s_{\mathrm{pkm\_active}})\big) + \big(\mathrm{VRU} * Q * s_{\mathrm{pkm\_active}}\big)\Big)/Q$, where VRU is the PST variable *unmotorised VRU crash rates*, "the injury crashes with unmotorised VRUs per mill. vehicle-kilometre driven". Lacking RSTE in the PST, we then let the derived RSTE from RSM (andy VRU) follow the growth over time of RSM (in freight transport scenarios). In the passenger car sub-use case involving road-use pricing (static toll and dynamic toll), we lack both RSTE and RSM. In that case, we apply VRU combined with a fixed RSM to derive RSTE, using the formula above. That is, instead of taking RSM from the PST, we insert a fixed PST default of 2.2 (crashes between motorised vehicles per mill. vkm). Lacking RSTE and RSM in the PST, we then let the derived RSTE from VRU (and a fixed RSM) follow the growth over time of VRU (for the road-use pricing SUC). Public transport vehicles (except AUSS) are not included in any of the PST crash rates; RSM only involves passenger cars and freight vehicles in freight transport scenarios; and only passenger cars in passenger transport scenarios. For VRU and RSTE, the active transport modes, cyclists and pedestrians, are added.

[48] Crashes involving MC/moped and all other transport modes are also omitted in all scenarios.

In this deliverable, we will (instead of 14,755) propose a rounded weighted average of 14,800 EUR$_{2020}$ per crash ($\bar{C}_{\text{crash}}$). The 17,000/30,500 GDP-downscaling, representing the initial default levels in PST/CBA, will then be approximately 8250 EUR$_{2020}$ (instead of 8224).

Estimating total crash numbers and total crash costs, for passenger transport scenarios and freight scenarios

From the number of crashes per vkm in the PST, we can estimate a total annual number of crashes in the selected geographical area, using either total pkm in passenger transport scenarios or total (freight and passenger) transport vkm in freight transport scenarios.

- In passenger transport scenarios, we derive vkm per transport mode using modal shares and occupancy; thus, total vkm is simply the sum across transport modes.
- In freight transport scenarios, total vkm for all freight in the given geographical area is available in the PST. As indicated above, in the CBA module we assume as a default that 10% of total vkm is freight (distributed 90-10 among LCV and HGV vkm), while the remaining 90% of vkm is distributed between public transport, passenger cars, and active transport. Applying default modal shares for passenger transport and their occupancies, we can derive modal shares of passenger transport vkm as well.

The total number of crashes is given from multiplying the crash rate per vkm by total road-based vkm by the included transport modes ($N_{\text{crash}} = n_{\text{crash\_Mvkm}} * T_{\text{safety}}$), either passenger cars, active transport, and (if relevant) shuttle-buses (for passenger transport scenarios, $T_{\text{safety\_passenger}}$), or passenger cars, active transport, and freight vehicles (for freight scenarios, $T_{\text{safety\_freight}}$). That total crash number can be multiplied by the average crash costs (14,800 EUR), yielding the total (annual) crash cost ($\bar{C}_{\text{crash}} * N_{\text{crash}}$). In the CBA module, the total cost of crashes is also attributed across the transport modes, which is explained more in detail below.

The external crash cost and internal crash cost per vkm, for different transport modes

Road safety impacts have an internal and an external part that we need to account for in the CBA. The internal part is the negative impact that the individuals inflict on themselves (in their mode choice and other risk-taking behaviour). The external part is what they inflict on others (on other road users and on third parties, e.g., the public health sector).[49] This is a main reason for the attribution of total crash costs across transport modes. Then we take into account that different transport modes have different shares of external versus internal costs in relation to crashes.

The share of external versus internal costs is primarily driven by the physical externality, the damage incurred on the counterpart in a crash (Rødseth et al. 2019, Ch. 7), which partly increases in the weight of the vehicle. Thus, HGVs and buses have higher shares of external costs than cyclists/pedestrians. The active transport users will also incur external costs, primarily system externalities, costs incurred on third parties (e.g., the public health sector).

[49] For further explanations of how to split the impacts into internal and external parts, see, e.g., Lindberg (2005) and Rødseth et al. (2019, Ch. 7).

Table 2.22 lists the external crash cost, the rate of external vs. internal costs, as well as the internal crash cost and the sum of external and internal, per transport mode. In addition, a relative crash cost figure is added. These estimates primarily follow van Essen et al. (2019), in EUR_{2016}, with some additional input from Rødseth et al. (2019, Ch. 7).

Table 2.22: External and internal crash costs per vkm

Transport mode	EU-28 - GDP/capita in EUR_{2020} (*30,500*)				Relative crash cost rate (vkm)
	External crash cost per vkm (EUR_{2020})	Share external vs. internal	Internal crash cost per vkm (EUR_{2020})	External+internal cost per vkm (EUR_{2020})	
Active transport	*0.0400*	*30%*	*0.0933*	*0.1333*	*0.0667*
Car, manual	*0.0800*	*50%*	*0.0800*	*0.1600*	*0.0800*
Car, automated, 1st gen.	*0.0400*	*50%*	*0.0400*	*0.0800*	*0.0400*
Car, automated, 2nd gen.	*0.0400*	*50%*	*0.0400*	*0.0800*	*0.0400*
Bus/coach (manual)	*0.1900*	*70%*	*0.0814*	*0.2714*	*0.1357*
Rail-based	*0.5000*	*70%*	*0.2143*	*0.7143*	*1.0000*
All public transport, manual (weighted average)	*0.2400*	*70%*	*0.1029*	*0.3429*	*0.4801*
Shuttle bus, 8 seats, manual (average of bus & car)	*0.0875*	*60%*	*0.0583*	*0.1458*	*0.0729*
Shuttle bus, 8 seats, automated	*0.0438*	*60%*	*0.0292*	*0.0730*	*0.0365*
Shuttle bus, 10 seats, manual (average of bus & car)	*0.0875*	*60%*	*0.0583*	*0.1458*	*0.0729*
Shuttle bus, 10 seats, automated	*0.0438*	*60%*	*0.0292*	*0.0730*	*0.0365*
Shuttle bus, 15 seats, manual (average of bus & car)	*0.0875*	*60%*	*0.0583*	*0.1458*	*0.0729*
Shuttle bus, 15 seats, automated	*0.0438*	*60%*	*0.0292*	*0.0730*	*0.0365*
LCV (manual)	*0.0410*	*60%*	*0.0273*	*0.0683*	*0.0342*
HGV (manual)	*0.1550*	*80%*	*0.0388*	*0.1938*	*0.0969*
Freight, manual (weighted average)	*0.0530*	*70%*	*0.0227*	*0.0757*	*0.0379*
LCV, automated	*0.0205*	*60%*	*0.0137*	*0.0342*	*0.0171*
HGV, automated	*0.0775*	*80%*	*0.0194*	*0.0969*	*0.0485*
Freight, automated (weighted average)	*0.0265*	*70%*	*0.0114*	*0.0379*	*0.0190*

Sources: Van Essen et al. (2019, Table 8); Rødseth et al. (2019, Tables 7.33 & 7.38), Elvik et al. (2020, Ch. 4.8.6).

From external crash cost estimates per vkm and the relative share of external versus internal crash costs, we can derive the internal crash cost estimates per vkm. From the sum of external and internal crash costs, we can derive the relative crash cost rate.

Costs per vkm for manual LCV and HGV are taken from van Essen et al. (2019); and the weighted average for all manual freight is based on the default distribution of 90% vkm by LCV and 10% vkm by HGV.

The estimate for active transport is based on the relative valuation with respect to motorcycles, combining estimates for active transport and motorcycles from Rødseth et al. (2019) with estimates for motorcycles from van Essen et al. (2019).

To derive crash cost estimates for automated shuttle-buses, we have applied virtual manual versions that are assumed to have costs that are simple averages of the crash costs for (large, manual) buses and (manual) cars, from van Essen et al. (2019).[50]

For automated vehicles, Elvik et al. (2020) present various estimates of safety improvements (crash risk reduction) from the literature. Based on his review, we have simply set the default cost estimate per vkm 50% lower for automated vehicles, comprising all types of automated cars, automated shuttle buses, and automated freight vehicles.

What we apply in the CBA calculations, in addition to the PST crash rate per vkm, are the vkm per transport mode, the average crash cost, and the relative crash cost rate for the transport modes that enter the crash cost calculations (manual and automated cars and active transport, plus either automated shuttle buses or freight vehicles).[51]

<u>Calculated crash costs under passenger transport scenarios and under freight transport scenarios</u>

As indicated above, the PST variable *road safety total effect* ("road safety effects when accounting for VRU and modal split") will have different content for passenger transport scenarios and for freight transport scenarios:

- Related to passenger transport sub-use cases (passenger car automation or urban mobility shuttle sub-use cases), the PST crash variable will comprise all crashes between passenger cars as well as crashes between passenger cars and cyclists/pedestrians. For shuttle-bus scenarios, also crashes between shuttle buses, between shuttle buses and cars, as well as between shuttle buses and cyclists/pedestrians, are included.
- Related to freight transport (freight and logistics sub-use cases), the PST crash variable will comprise all crashes between passenger cars as well as crashes between freight vehicles, crashes between freight vehicles and passenger cars, crashes between freight vehicles and cyclists/pedestrians, and crashes between passenger cars and cyclists/pedestrians.

[50] Public transport is not included in the Levitate road safety impact calculations, but we have included the estimated crash costs for rail (passenger trains) and bus transport based on van Essen et al. (2019). We have also estimated cost figures for all public transport as a vkm-weighted average of bus (85%) and rail-based transport (15%). In our CBA, we generally assume that LEVITATE policy scenarios have no direct impact on rail-based transport.

[51] The current initial PST default average crash rate (RSTE), at the time of writing this deliverable, is 0.86 crashes per million vkm.

Formulas for calculating crash costs under passenger transport scenarios and under freight transport scenarios

The road safety cost calculations can be described applying formulas. As clarified above, there are two types of calculation approaches, one for passenger transport scenarios and one for freight transport scenarios.

For passenger transport scenarios, our point of departure is the estimated vkm for passenger cars and active transport (estimated for the reference, $T^0_{\text{safety\_passenger}}$, and the policy scenario, $T^1_{\text{safety\_passenger}}$), including also AUSS vkm if this use case is involved:

$$T_{\text{safety\_passenger}} = T_{\text{mancar}} + T_{\text{autcar}} + T_{\text{active}} + T_{\text{autshuttle}}$$

in combination with their relative crash cost rate per vkm ($\bar{\theta}_{\text{crash}}$). This is applied with the average crash cost ($\bar{C}_{\text{crash}}$) and the number of crashes (N_{crash}). That is, e.g., for manual cars:

$$\tilde{C}_{\text{crash\_mancar}} = \bar{C}_{\text{crash}} * N_{\text{crash}} * \left(\frac{T_{\text{mancar}}}{T_{\text{safety\_passenger}}}\right) * \bar{\theta}_{\text{crash\_mancar}}$$

This product is then scaled to the sum of (annual) total crash costs ($\bar{C}_{\text{crash}} * N_{\text{crash}}$) under the passenger transport scenario. That is:[52]

$$C_{\text{crash\_mancar}} = \tilde{C}_{\text{crash\_mancar}} * \left(\frac{\bar{C}_{\text{crash}} * N_{\text{crash}}}{\tilde{C}_{\text{mancar}} + \tilde{C}_{\text{autcar}} + \tilde{C}_{\text{active}} + \tilde{C}_{\text{autshuttle}}}\right)$$

The crash cost per vkm for manual cars ($c_{\text{crash\_vkm\_mancar}}$) is obtained simply by dividing $C_{\text{crash\_mancar}}$ by the manual car transport distance in vkm, T_{mancar}:[53]

$$c_{\text{crash\_vkm\_mancar}} = \frac{C_{\text{crash\_mancar}}}{T_{\text{mancar}}}$$

The differentiation between external crash costs and internal crash costs is based on a fixed share of external crash costs per transport mode (Table 2.22), e.g., for manual cars, $\bar{\alpha}_{\text{ext\_crash\_mancar}}$=0.5.

For freight transport scenarios the calculations are nearly the same; our point of departure is the estimated vkm for freight vehicles, passenger cars, and active transport:

$$T_{\text{safety\_freight}} = T_{\text{manfreight}} + T_{\text{autfreight}} + T_{\text{mancar}} + T_{\text{autcar}} + T_{\text{active}}$$

in combination with their relative crash cost rate per vkm ($\bar{\theta}_{\text{crash}}$). This is applied with the average crash cost ($\bar{C}_{\text{crash}}$) and the number of crashes (N_{crash}). That is, e.g., for automated freight vehicles:

$$\tilde{C}_{\text{crash\_autfreight}} = \bar{C}_{\text{crash}} * N_{\text{crash}} * \left(\frac{T_{\text{autfreight}}}{T_{\text{safety\_freight}}}\right) * \bar{\theta}_{\text{crash\_autfreight}}$$

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[52] Obviously, $\bar{C}_{\text{crash}} * N_{\text{crash}} = C_{\text{crash\_mancar}} + C_{\text{crash\_autcar}} + C_{\text{crash\_active}} + C_{\text{crash\_shuttle}}$ under passenger transport scenarios. Furthermore, we have that $n^{\text{crash/vkm}} * T = N_{\text{crash}}$.

[53] Dividing $c_{\text{crash\_vkm\_mancar}}$ by the occupancy ($n_{\text{occ\_mancar}}$) yields the crash cost per pkm; thus, e.g.: $c_{\text{crash\_pkm\_mancar}} = \frac{c_{\text{crash\_vkm\_mancar}}}{n_{\text{occ\_mancar}}}$.

This product is then scaled to the sum of (annual) total crash costs ($\bar{C}_{\text{crash}} * N_{\text{crash}}$) under the freight transport scenario. That is:[54]

$$C_{\text{crash\_autfreight}} = \tilde{C}_{\text{crash\_autfreight}} * \left(\frac{\bar{C}_{\text{crash}} * N_{\text{crash}}}{\tilde{C}_{\text{manfreight}} + \tilde{C}_{\text{autfreight}} + \tilde{C}_{\text{mancar}} + \tilde{C}_{\text{autcar}} + \tilde{C}_{\text{active}}}\right)$$

The crash cost per vkm for automated freight vehicles ($c_{\text{crash\_vkm\_autfreight}}$) is then given directly, dividing $C_{\text{crash\_autfreight}}$ by the transport distance in vkm, $T_{\text{autfreight}}$:

$$c_{\text{crash\_vkm\_autfreight}} = \frac{C_{\text{crash\_autfreight}}}{T_{\text{autfreight}}}$$

Also in the freight transportation scenario case, the differentiation between external crash costs and internal crash costs is based on a fixed share of external crash costs per transport mode (Table 2.22), e.g., for automated freight vehicles, $\bar{\alpha}_{\text{ext\_crash\_autfreight}}$=0.7.[55] Thus, the calculations across transport modes will partly enter infrastructure users' internal costs and partly enter external costs that affect others (M_{external}).

Emissions

Emissions of NO_X, PM_{10} and CO_2, in gram per vkm

Emissions are expressed in the PST by *NO_X due to vehicles*, *PM_{10} due to vehicles*, and *CO_2 due to vehicles*; all measured in g/vkm. These are emissions produced by all types of motorised transport modes on the road. These variables ($\overline{\mathrm{NO}}_X^{g/vkm}$, $\overline{\mathrm{PM}}_{10}^{g/vkm}$, and $\overline{\mathrm{CO}}_2^{g/vkm}$) are defined in the same way, in the PST, whether the focus is on passenger cars, shuttle buses or freight vehicles.[56]

(Relative) costs of NO_X, PM_{10} and CO_2 per vkm for different transport modes

For the monetising of these effects, our point-of-departure is the listing of costs of emissions per vkm per transport mode in van Essen et al. (2019, Tables 16 and 25). They include more air pollutants than the PST. In our listing of emission costs per mode, we have simply downscaled the cost estimates for NO_X and PM_{10} with respect to their relative values (van Essen et al. 2019, Table 14). Costs per vkm for NO_X, PM_{10}, and CO_2 equivalents, for different transport modes, have also been GDP-updated from EUR_{2016} to EUR_{2020} (30,500/29,310).

It is assumed that all automated vehicles will be electric vehicles, having no CO_2 emission under transport and reduced emissions of NO_X and PM_{10}. We apply an estimate of 50% less emissions of NO_X and PM_{10} from (automated) electric vehicles, based on estimates from Rødseth et al. (2019). The estimates for trains, from van Essen et al. (2019) are

[54] Obviously, $\bar{C}_{\text{crash}} * N_{\text{crash}} = C_{\text{crash\_manfreight}} + C_{\text{crash\_autfreight}} + C_{\text{crash\_mancar}} + C_{\text{crash\_autcar}} + C_{\text{crash\_active}}$ under freight transport scenarios.

[55] As the inputs to the CBA comprises crash rates per vkm and transport distance, the marginal crash cost per transport mode (or average crash cost per transport mode, disregarding traffic-volume externality) will be an output variable in the CBA calculations. The average cost per crash (the injury severity distribution) as well as the relative crash cost weights, across transport modes, are fixed.

[56] In one passenger car sub-use case, involving road-use pricing (static toll and dynamic toll), emissions are not included. In that case we apply PST default emissions; for PM_{10} 0.2 g/vkm, for NO_X 1.8 g/vkm, for CO_2 2500 g/vkm.

assumed to apply to all rail-based transport, and all (urban) passenger train transport is assumed to be electric. We add the relative costs for our selected transport modes, based on the cost estimates per vkm from van Essen et al. (2019) and additional information from Rødseth et al. (2019).

Table 2.23: External costs of air pollution (NO_X and PM_{10}) and greenhouse gases (CO_2 equivalents)

Transport mode	**EUR_{2020}/vkm**			**Relative NO_X emission cost**	**Relative PM_{10} emission cost**	**Relative CO_2 emission cost**
	NO_X	**PM_{10}**	**CO_2**			
Car, manual (primarily petrol & diesel)	*0.0013*	*0.0013*	0.0198	*0.08*	*0.08*	*0.22*
Bus (manual, primarily diesel)	*0.0159*	*0.0166*	0.0919	*1.00*	*1.00*	*1.00*
Shuttle bus, manual (simple average of bus and car)	*0.0086*	*0.0090*	*0.0558*	*0.54*	*0.54*	*0.61*
Train (electric)	*0.0013*	*0.0013*	0.0000	*0.08*	*0.08*	*0*
Public transport (weighted average)	*0.0137*	*0.0143*	*0.0781*	*0.86*	*0.86*	*0.85*
LCV, manual	*0.0036*	*0.0038*	0.0286	*0.23*	*0.23*	*0.31*
HGV, manual	*0.0105*	*0.0110*	0.0674	*0.66*	*0.66*	*0.73*
Freight (manual, simple average of HGV and LCV)	*0.0071*	*0.0074*	*0.0480*	*0.44*	*0.44*	*0.52*
Automated electric LCV	*0.0018*	*0.0019*	*0.0000*	*0.11*	*0.11*	*0*
Automated electric HGV	*0.0052*	*0.0055*	*0.0000*	*0.33*	*0.33*	*0*
Automated electric freight (simple average)	*0.0035*	*0.0037*	*0.0000*	*0.22*	*0.22*	*0*
Automated electric car	*0.0006*	*0.0007*	*0.0000*	*0.04*	*0.04*	*0*
Automated electric shuttle bus	*0.0043*	*0.0045*	*0.0000*	*0.27*	*0.27*	*0*

Sources: Van Essen et al. (2019, Tables 14, 16 & 25); Rødseth et al. (2019, Tables 2, 3 & 4).

The average cost per gram emissions of NO_X, PM_{10} and CO_2

The PST variable yields emissions of NO_X, PM_{10}, and CO_2 in weight per vkm for all road-based transport in total. Thus, we will "distribute" total emission costs among the transport modes, combining the transport modes' relative cost estimates (from Table 2.23) and costs per kilogramme emission from van Essen et al. (2019, Table 14, p. 55-56, and Table 24, p. 78), that we state in costs per gram emission ($c^{\mathrm{g}}_{\mathrm{NO_X}}$, $c^{\mathrm{g}}_{\mathrm{PM_{10}}}$, and $c^{\mathrm{g}}_{\mathrm{CO_2}}$).

Table 2.24 lists the average costs per gram of emission. Van Essen et al. (2019) differentiate the CO_2 equivalent price over time, in short term (2020-2030) and long-term (2040-2060); we have set the medium term (2030-2040) as an average of the two.

Table 2.24: External costs of air pollution (NO_X and PM_{10}) and greenhouse gases (CO_2 equivalents), EUR_{2020} per gram emission.

	NO_X	PM_{10}	CO_2 2020-2030	CO_2 2030-2040	CO_2 2040-2050
EU-28 - GDP/capita in EUR_{2020} (*30,500*)	0.022165	0.023205	0.000104	*0.000192*	0.000280
PST/CBA initial default GDP/capita in EUR_{2020} (17,000)	0.012354	0.012934	0.000058	*0.000107*	0.000156

Source: Van Essen et al. (2019, Tables 14 & 24).

Formulas for calculating emission costs under passenger transport scenarios and under freight transport scenarios

The CBA calculations can be described using formulas. What is provided from the PST is the average emissions in grams of NO_X, PM_{10}, and CO_2 per vkm. Thus, the (annual) total cost of these emissions is equal to the emission per vkm (e.g., $\overline{NO}_X^{g/vkm}$) times cost per gram ($c_{NO_X}^{g}$) times vkm of the vehicles emitting NO_X, PM_{10}, and CO_2 (T_{emission}). For NO_X and PM_{10}, $T_{\text{emission\_local}} = T - T_{\text{active}}$; while in the case of carbon dioxide (equivalents), $T_{\text{emission\_global}} = T_{\text{mancar}} + T_{\text{public}} + T_{\text{manfreight}}$.

The emission quantities per vkm in PST applies to both passenger transport and freight transport. Thus, in the CBA module we apply the specified default for involving both types of transport even if only one is specified; either a passenger transport scenario not specifying freight, or a freight transport scenario not specifying passenger transport.

The emission costs per transport mode (e.g., emission of NO_X from manual passenger cars, equal: total cost of emissions ($C_{NO_X}^{0}$), times mode share of vkm ($\frac{T_{\text{mancar}}}{T_{\text{emission\_local}}}$), times the relative emission cost factor ($\bar{\theta}_{NO_X\text{\_mancar}}$); that yields a product that is scaled (by a variable factor) to the sum of total emission costs. That is, e.g., for manual passenger cars:

$$\tilde{C}_{NO_X\text{\_mancar}} = \left(\left(\overline{NO}_X^{g/vkm} * c_{NO_X}^{g} * T_{\text{emission\_local}} \right) * \left(\frac{T_{\text{mancar}}}{T_{\text{emission\_local}}} \right) * \bar{\theta}_{NO_X\text{\_mancar}} \right)$$

and

$$C_{NO_X\text{\_mancar}} = \tilde{C}_{NO_X\text{\_mancar}} * \left(\frac{\overline{NO}_X^{g/vkm} * c_{NO_X}^{g} * T_{\text{emission\_local}}}{\tilde{C}_{NO_X\text{\_mancar}} + \tilde{C}_{NO_X\text{\_autcar}} + \tilde{C}_{NO_X\text{\_public}} + \tilde{C}_{NO_X\text{\_shuttle}} + \tilde{C}_{NO_X\text{\_manfreight}} + \tilde{C}_{NO_X\text{\_autfreight}}} \right)$$

while $\tilde{C}_{NO_X\text{\_active}}$ is always zero.

The formulas will have exactly the same structure for emissions of PM_{10}; in general, also for CO_2, but then involving fewer transport mode types.

The formulas presented above will also have the same structure for all specified transport modes. The calculations across transport modes will enter the external costs that affect the rest of the society (M_{external}).

Parking space

The variable *parking space*, the "required parking space in the city centre per person" ($\bar{a}_{\text{pop\_parking\_sqm}}$), is measured in m²/person. It can be multiplied by the PST variable *city population* (POP) for an estimate of the city centre parking space (in m²), ($A_{\text{parking\_sqm}}$).[57]

To monetise this effect, we apply a default value that represents the approximate square metre value of (undeveloped, unconstructed) land in the more urban areas of Europe. Combes et al. (2019) analysed land prices in France. They show an interval of 255-321 EUR per square metre as «mean land prices 2006-2012», in the major city areas of France. Taking into account the GDP level in France in 2006-2012, we propose 300€ (for GDP/capita=30,500 EUR_{2020}; or 161.21€ for GDP/capita=17,000 EUR_{2020}) as a default value per square metre (undeveloped/unconstructed) land in major European cities ($p_{\text{land\_sqm}}$).[58]

Regarding parking fees in European cities, the average was about 3 EUR/hour some few years ago (in 2016).[59] The fees varied considerably, of course, from 0.50 in Sofia and just above 1 in Warsaw, up to about 8 EUR/hour in London and Stockholm. We apply 3 EUR_{2020} as default parking fee per hour, representing the EU-28 cost level of GDP/capita average of 30,500 EUR_{2020}. The default parking fee per hour ($p_{\text{fee\_parking}}$) will then be 1.67 EUR/hour for the default PST/CBA GDP/capita of 17,000 EUR_{2020}. We set the average parking duration ($h_{\text{hour\_parking}}$) in centric areas, for all types of activities (including work), to 4 hours (Bates & Leibling 2012).

Commuting distances

Average length of trips to and from work (added together) is expressed in the PST by the variable *commuting distances*. Divided by two it yields the average length of a commuting single trip ($\bar{T}_{\text{trip\_commute}}$). As a simplification, we also apply this trip length for travel having other purposes ($\bar{T}_{\text{trip}} = \bar{T}_{\text{trip\_commute}} = \bar{T}_{\text{trip\_other}} = \bar{T}_{\text{trip\_business}}$). We apply average trip length primarily for deriving an estimation of the total number of passenger trips by public transport ($n_{\text{trip\_public}} = Q_{\text{public}}/\bar{T}_{\text{trip}}$).

The number of trips by public transport can be applied for calculating ticket costs (per km) for public transport users, as well as calculating the ticket income for the public transport providers. The same approach is our default for automated shuttle buses.

We also apply trip length for some passenger car sub-use cases; in those cases, not car passenger (incl. driver) trips, but car trips ($n_{\text{trip\_car}} = T_{\text{car}}/\bar{T}_{\text{trip}}$).

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[57] Total parking space divided by parking area per vehicle (say 20m²) yields a simplistic estimate of the parking lot capacity, which also could provide a crude estimate of fee payment (disregarding that the real vehicle number fluctuates below full capacity, that more than one vehicle might use a given lot during the day, and that one particular vehicle might use more than one parking lot during the day).

[58] If we include, in the CBA module, the land price times demanded parking space from PST, we implicitly assume that any change in required parking space can enable an alternative use of the previous parking space. That might not be obvious, yet the land transaction value change between baseline and policy will be singled-out in the CBA results, such that its relative impact is visible for the user.

[59] This estimate is due to https://www.euronews.com/2016/05/10/the-cost-of-parking-across-europe-a-euronews-investigation, retrieved 22nd of March 2022.

Additional user input to the CBA

All changes to PST default values that the PST user has inserted will be brought over to the CBA module, by default. However, the user can adjust the CBA input, the cost of implementing the policy,[60] as well as the valuations of impacts.

The PST analysis period is default for the CBA; and an initial year set by the user (say 2025) and a default end year (2050) is brought forward. However, in the CBA module, the user will be asked to insert the project lifetime of their selected policy, X years. This will yield a final year of the project that might differ from 2050. If the implied project lifetime ends before 2050, there will be no cash flow (benefit-cost) calculations for the final years in the PST default horizon. If the project lifetime implies a final year beyond 2050, and the policy measure still yields a benefit flow for the society after 2050, a calculation of a residual value for the net benefit flow after 2050 is possible (though no impacts are foreseen in the PST). The residual value is thus the net benefit that the policy measure yields in the years from the end of a fixed project period, 2050 in our case, to the end of the lifetime of the particular installation or policy.

2.3 CBA functionalities

Main structure

The CBA module will be structured according to the set of relevant transport users/providers, the wider community, and an entity that represents the infrastructure owner (e.g., the public sector). There will be a common CBA structure for all classes of sub-use cases (urban public transport, passenger cars, and freight & logistics). Two of the transport service providers will only appear in specific sub-use cases: automated urban transport service (AUSS) shuttle buses and automated freight-transport providers. Impacts for passenger cars appear under all three classes of sub-use cases, not just the ones particularly for passenger cars. Impacts for public transport (beyond automated shuttle buses) are handled in the sub-use cases for passenger cars. Impacts for active transport (cyclists and pedestrians) are also included to the extent that its modal share is included in the PST, but various sub-use cases are not expected to yield an effect on active transport (implying no difference between reference scenario and policy scenario).

The effect of the implementation of sub-use cases (policy measures) for the transport users are estimated as changes in consumer surplus (the difference between the willingness to pay for the travel and the generalised cost of travel). For the transport service providers, a (simplified measure of) producer surplus (the difference between the revenue of a service, e.g., ticket price times no. of passengers, and the cost of providing the service) is applied. The following internal costs/valuations are entered into these calculations:

- Vehicle operating and ownership costs (incl. depreciation function); for transport service providers also time-dependent operation/ownership costs
- Value of travel time savings

[60] Default estimates of the cost of implementing policy scenarios, SUCs (investments and/or management/maintenance costs), are provided within WP5, WP6, WP7.

- Internal cost of congestion (delay that the infrastructure user inflicts on himself / herself)
- Internal cost of traffic injury (the injury suffering and outlays that the infrastructure user inflicts on himself / herself)
- Ticket prices
- Road-use pricing (if the relevant SUC is chosen, if not, this is zero)

The transport modes "produce" external effects, whether it is on other infrastructure users or on the rest of the society; third parties (e.g., public setor), local and global inhabitants. The following external costs are applied in these calculations:

- Air pollution (NO_X, PM_{10}) costs
- Greenhouse gas (CO_2 equivalent) costs
- External congestion cost (the delay costs that the infrastructure user inflicts on other infrastructure users and the rest of society)
- External cost of traffic injury (the injury suffering and outlays that the infrastructure user inflicts on other infrastructure users as well as on the rest of society)

There is some entity that implements the policy scenarios, the public sector, another infrastructure owner, or transport service providers. The following impacts are placed under this "policy entity":

- Value of city space (area used for parking or other purpose)
- Income from various road-use pricing schemes
- Tax-financing cost

The costs of implementing the sub-use cases are also placed under the policy entity.[61]

CBA additionalities

As indicated above, the CBA module will enable (automatic) calculation of residual values, if the user indicates a final year of the policy measure lifetime which is beyond 2050. A break-even analysis will also be performed; it will show in which year the sub-use case will yield a positive net present value (if indeed it will happen).

Sensitivity analyses will also be implemented with respect to the inputs/outputs that are part of the PST calculations. These comprise the amount of travel, emissions, crashes, travel time, and (possibly) empty driving. The sensitivity analysis will show the estimated net benefits under varying assumptions for the calculations, typically a lower estimate than the given point estimate and a higher one (e.g., ±50%). We will disregard potential uncertainty in the more global figures, like future GDP development, future discount rates, future valuations of impacts, etc.

CBA for single SUC or combined SUC

To the extent that the PST provides one matrice of impacts and years for the policy scenario and one for the baseline scenario, whether it is a single SSUC or two SSUCs (combined SUC), the CBA handling is in principle the same. The challenge for the

[61] The CBA will compare policy implementation costs against all valued impact differences (positives as well as negatives) between the policy scenario and the baseline scenario (for the policy entity, transport users, transport service providers, and the external impacts).

PST/CBA module, for combined SUCs, is more of a combinatorial problem; the large increase in possible combinations.

2.4 Use cases

2.4.1 Structures

The PST has three different classes of use cases (policy scenarios): (i) passenger cars, (ii) urban transport (shuttle buses), and (iii) freight & logistics. For all three there are sets of various sub-use cases, or types of policy scenarios. Some of the sub-use cases will have a variation of specifications.

The three classes of use cases will have partly common sets and partly different sets of variables that are activated (included) in the policy versus reference scenario. The first two classes focus on passenger transport. Freight & logistics differ most from the two others. Notwithstanding, it is found more advantageous to include all three classes in one common CBA module. To some extent the specific PST variables will have different coverage across the sub-use cases, but such challenges can be handled within the common CBA module. The reference scenario, for a given geographical area, will be the same for all three classes of sub-use cases. The automation level will be the same for the reference scenario ("no automation", "pessimistic", "neutral", "optimistic") and the scenario of the sub-use case implementation (policy scenario).

2.4.2 The cost of implementing use-cases, implementing policy scenarios (the "cost side" of the CBA)

This deliverable does not cover estimation of the implementation costs of the use cases, the costs of implementing policy. Estimating the costs of implementation for all Levitate sub-use cases is not a simple task; neither the delimitation of cost elements nor the delineation of cost structure that is appropriate for varying scales.

Regarding the cost elements, we would propose disregarding legal preparations. For instance, legal labour costs comprised a considerable share of the costs of the Stockholm congestion charge, but supposedly some of the legal framework is now established.[62] Also the required quality, e.g., the required precision of the selected policy instrument, might in some cases have a considerable impact on the implementation costs. But in any case, there is a start-up cost that involves planning and preparation (labour costs), before reaching the stage of fieldwork and purchase/installation of technical equipment.

The CBA module, as the PST, is a generalised policy tool that should be applicable to different areas of different size. Thus, the implementation cost structure should also cater for that. That is, the function for the cost of implementation should preferably include a variable cost element that varies with respect to some physical measure, whether that is the size of the area, the number of vehicles involved, or whatever relevant. Commonly,

[62] In the Stockholm congestion charge case, the start-up costs amounted to as much as 180 million EUR, while the annual operation costs were about 20 million EUR (Eliasson 2009). Eliasson (2010) and Hamilton (2010) indicated that both start-up costs and operation costs could have been decreased substantially, primarily if the service level target were set lower than 99.9%.

such cost functions will be split between a fixed part (reflecting start-up costs and operation that do not vary with project size) and a variable part that depends on the size of the implemented use case.[63]

2.4.3 Monetised impacts (the "benefit side" of the CBA)

In general, the sub-use cases will not affect only the particular transport mode that is targeted (automated urban shuttle buses, automated passenger cars, or automated freight vehicles). Some sub-use cases will affect the modal split in passenger transport (public transport, active transport, and car-based transport). There might also be impacts on congestion, road safety (crash rates), and emissions, that subsequently affect other road users and the surrounding community. By calculating the monetised impacts of all these agents together, we take account of such "spill-over effects".

It should be stressed that the CBA module is a "static" add-on to the PST. The CBA does not include behavioural effects as such; the behaviour is modelled within the microsimulations, the mesoscopic modelling, and the system dynamics.

In the remainder of this section, we will describe shortly how the sub-use cases are handled in the CBA module; describing primarily the handling of the "benefit side" of the CBA, the monetised impacts.

2.4.4 The three classes of use cases and their sub-use cases

Urban transport (shuttle bus) use case
The urban transport (shuttle bus) sub-use cases are listed in Table 2.25 (Roussou et al. 2021a, b, c):[64]

As indicated, for the urban transport sub-use cases, we could assume that the proposed automated urban shuttle service (AUSS) represented entirely new services, not directly replacing existing public transport or taxi services. That is, the AUSS would be complements to existing services (Roussou et al. 2021a). That could have a bearing on how we handle the implementation of these sub-use cases in the CBA. We could have put the costs of acquiring and operating shuttle buses under the costs of implementation. However, for the sake of handling shuttle buses in the same way as other modes, we

[63] E.g., the form of the start-up cost could be: $\bar{C}_{\text{PI\_plan}} + c_{\text{PI\_plan}} * x + \bar{C}_{\text{PI\_field}} + c_{\text{PI\_field}} * x + c_{\text{PI\_equip}} * x$, where PI refers to policy implementation, $\bar{C}_{\text{PI}}$ refers to the fixed cost, c_{PI} the variable cost, x is the unit of what drives the variable cost (e.g., size of area, road length, or traffic quantity), and plan, field, equip refer, respectively, to the initial/general planning and design work, the initial fieldwork, and the equipment/installations needed. Possibly, the initial/general planning could include initial fieldwork, such that the formula simplifies to, e.g.: $\bar{C}_{\text{PI\_plan}} + c_{\text{PI\_plan}} * x + c_{\text{PI\_equip}} * x$. And, possibly, the costs might vary only with respect to a number of technical installations, such that the formula simplifies to: $\bar{C}_{\text{PI\_plan}} + c_{\text{PI\_equip}} * x$. The format of the annual operation costs for the policy implementation (use case operation) can have the same format as the start-up ("investment"), differentiating between fixed costs and variable costs.

[64] An underlying assumption in the PST, and hence in the CBA, is that only automated shuttle buses (as specified within this class of sub-use cases) will represent the automation in public transport.

place the vehicle operation and ownership costs on the "benefit" side, which in this case will be the monetisation of the impacts for transport service providers.[65]

A related issue for the CBA module is that automated shuttle sercices will represent a new transport mode. Thus, we can only estimate the travel by automated shuttles and the generalised costs under the policy scenario, not the baseline (reference) scenario. Yet, the CBA calculations for transport consumers are mode-based, comparing the travel by a transport mode and the genarlised costs of that mode in the policy scenario against the baseline. We propose a specific approach for the handling of this particular issue, under section **Error! Reference source not found.**, below.

Table 2.25: Urban transport sub-use cases – automated urban shuttle service (AUSS)

Urban transport sub-use cases	Description
Point-to-point AUSS	**Point-to-point AUSS connecting two modes of transport**: Shuttle bus connecting the metro station and the intercity main bus terminal. **Point-to-point AUSS in a large-scale network**: Shuttle bus lines with various fixed stations complementing the existing public transport.
On-demand AUSS	Autonomous shuttle bus fleet, complementing the existing public transport, includes three sub-scenarios (sub-sub-use cases): anywhere to anywhere service, last mile service, and e-hailing services. • Anywhere to anywhere service: automated shuttles travelling between different non-fixed locations • Last-mile service: automated shuttles providing convenient first/last mile solutions, complementing public transport • E-hailing: on-demand last mile automated shuttles booked by multiple passengers to travel between convenient points

Sources: Roussou et al. (2021a, b, c).

The automated urban shuttle service will consist of two main types, a point-to-point "public transport type" and an "on-demand shared taxi" type. For both types, the automated shuttle travel will be part of the public transport share of the amount of travel (pkm) in the PST.

<u>Point-to-point AUSS – connecting two public transport modes</u>
Firstly, the point-to-point AUSS between two hubs can be specified for various combinations of traffic conditions (peak hours vs. off-peak hours) and section features (dedicated lane vs. running in mixed traffic); that is, four combinations plus an "incident" scenario, a blocked road segment during peak hours (Roussou et al. 2021b). The selected combination might affect the monetised impacts of the sub-use case.

[65] In terms of estimated net benefits of the policy, placing the cost of shuttles (the vehicle operating and ownership costs) on the benefit-side (instead of the cost-side) will not change the conclusions from the CBA; but it might affect the estimation of benefit-cost ratios.

Regarding implementation costs, the costs (start-up and operation) will possibly vary with respect to the size of the shuttle-bus project (distance between points, possibly also the frequencies / no. of shuttle buses in operation). We would assume initial planning/preparation (and fieldwork) costs and possibly labour costs in operation (beyond the particular operation of the automated shuttles; with 10 passenger capacity).

We present, in a table below, the elements that are applied for the CBA calculations (in addition to the specification of vehicle and operating costs, as proposed in Table 2.12 and

Table 2.13). We assume that the point-to-point AUSS enters as part of public transport, applying the existing ticket system within the selected area.

Point-to-point AUSS – large-scale network

The point-to-point AUSS in large-scale network can also be specified for various combinations of traffic conditions (peak hours vs. off-peak hours) and section features (dedicated lane vs. mixed traffic); that is, three combinations, as dedicated lane is only combined with peak hour traffic conditions (Roussou et al. 2021b). The selected combination might affect the monetised impacts of the sub-use case.

The handling of point-to-point AUSS in a large-scale network is in principal the same in CBA as point-to-point AUSS between only two points. Thus, regarding implementation costs (start-up and operation), these will most probably vary with respect to the size of the shuttle-bus project (the no. of point-to-point sections, etc.). We would assume initial planning/preparation (and fieldwork) costs and possibly some additional labour costs of operation (beyond the particular operation of the shuttles, with 10 passenger capacity).

We present, in a table below, the elements that are applied for the CBA calculations (in addition to the specification of vehicle and operating costs, as proposed in Table 2.12 and

Table 2.13). As indicated above, we assume that the point-to-point AUSS will enter as part of the public transport, that users of point-to-point automated shuttles apply the existing ticket system within the selected area.

<u>On-demand AUSS</u>
Firstly, the on-demand AUSS can be specified for different combinations of the share of demand served (5% or 10%) and shuttle-bus type (capacity of 8 or 15 passengers); four combinations in total (Roussou et al. 2021b). The selected combination might affect the monetised impacts of the sub-use case.

Regarding implementation costs (start-up and operation), these will vary with respect to the size of the shuttle-bus project. We would assume initial planning/preparation (and fieldwork) costs and possibly some additional labour costs of operation (beyond the particular operation of the shuttles, with 8 or 15 passenger capacity).

We present, in a table below, the elements that are applied in the CBA calculation (in addition to the specification of vehicle and operating costs, as proposed in Table 2.12 and

Table 2.13).

In general, we consider that the three types of on-demand services can be handled in the same way within the CBA: "from-anywhere-to-anywhere shuttles", (first and/or) "last-mile shuttle", and "e-hailing" (which might also be a type of last-mile service).[66] The pkm of automated on-demand shuttles will be included in the public transport share of the amount of travel, in the PST. As a paid service, automated on-demand services will resemble shared taxis, including the ride sharing under automated passenger car sub-use cases (see below). Beyond that, the PST output in combination with proposed valuations will govern the monetised impacts.

Summarising particular input to CBA approach for AUSS sub-use cases

The following table summarises the additional AUSS-sub-use-specific input that we apply (Roussou et al. 2021a, 2021b), in addition to standard PST input. In addition, for point-to-point services, the operation hours are 20 hours with 15 min. (0.25 h) service frequency; and the section lengths are 3.4 and 7 kms, respectively for connecting two modes and for (average length of) sections in a large-scale network.

Table 2.26: Particular input to CBA of sub-use cases under auomated urban shuttle service (AUSS)

Shuttle-bus input	**General assumptions**			**Assumed, applied or derived figures**						**PST scale**	
	fleet size	**seat capa-city**	**occu-pancy rate**	**occu-pancy**	**trip dist. (km)**	**daily fleet rides**	**daily pass. no.**	**daily fleet vkm**	**daily fleet pkm**	**daily amount of travel (pkm)**	**share AUSS fleet pkm**
Point-to-point AUSS											
- connecting two modes	*4*	*10*	*50%*	*5.0*	*3.40*	*80*	*400*	*272*	*1360*	*1,820,602*	*0.07%*
- in large-scale network	*16*	*10*	*50%*	*5.0*	*7.00*	*80*	*400*	*560*	*2800*	*2,173,004*	*0.13%*
On-demand AUSS											
sub-sub 1	*50*	*8*	*50%*	*4.0*	*4.32*	*85*	*338*	*365*	*1460*	*2,173,004*	*0.07%*
sub-sub 2	*50*	*15*	*50%*	*7.5*	*6.41*	*45*	*338*	*289*	*2168*	*2,173,004*	*0.10%*
sub-sub 3	*100*	*8*	*50%*	*4.0*	*3.80*	*227*	*909*	*863*	*3452*	*2,173,004*	*0.16%*
sub-sub 4	*100*	*15*	*50%*	*7.5*	*4.65*	*121*	*909*	*564*	*4230*	*2,173,004*	*0.19%*

Sources: Roussou et al. (2021a, b).

The derived pkm for AUSS ($Q_{\text{autshuttle8}}$, $Q_{\text{autshuttle10}}$, or $Q_{\text{autshuttle15}}$) is already included in the PST variable *amount of travel*. Thus, the remaining public transport (bus and rail-based) is derived by subtracting AUSS pkm from the *amount of travel* (Q) times the *modal split of travel using public transport* ($s_{\text{pkm\_public}}$). E.g., for on-demand 8-seats automated shuttle case: $Q^{\text{AUSS8}}_{\text{other\_public}} = Q_{\text{public}} - Q_{\text{autshuttle8}}$, where $Q_{\text{public}} = Q * s_{\text{pkm\_public}}$.

[66] On-demand AUSS, particularly the e-hailing, resembles automated ride sharing of the type "shared automated taxis", but will involve vehicles that are larger than ordinary passenger cars, i.e., shuttles with seat capacity for 8 or 15 passengers.

The AUSS figures in Table 2.26 represent levels for a given *amount of travel*, the travel by public transport (including AUSS, under policy scenario), passenger cars, and active travel, in passenger km (pkm). The PST variable *amount of travel* will be applied for scaling the AUSS pkm and subsequent passenger numbers, vkm, etc. The scaling parameters, the AUSS pkm percentage of the *amount of travel*, differ somewhat between the AUSS scenarios: $\alpha_{\text{autshuttle10\_small}} = 0.07\%$, $\alpha_{\text{autshuttle10\_large}} = 0.13\%$, $\alpha_{\text{autshuttle8\_sub1}} = 0.07\%$, $\alpha_{\text{autshuttle15\_sub2}} = 0.10\%$, $\alpha_{\text{autshuttle8\_sub3}} = 0.16\%$, and $\alpha_{\text{autshuttle15\_sub4}} = 0.19\%$.

At the time of writing the deliverable, we have no default figures for the costs of implementing the AUSS sub-use cases. In the CBA module we will set a (fixed) default of €1 million in start-up costs and €10,000 in annual operation costs (for GDP/capita equal to 30,500 EUR_{2020}). Remark that these are costs of implementation (planning/preparation and current management) that are NOT included in the vehicle operation and ownership costs. The scaling of the costs of implementation may implicitly follow the same approach as described above; that is, a higher *amount of travel* will imply higher costs of implementation (although part of these costs might be fixed, not variable with respect to the extent of the AUSS service).

Passenger car use case

The passenger car sub-use cases (Haouari et al. 2021, Sha et al. 2021, Chaudry et al. 2021) are listed in Table 2.27.

Table 2.27: Passenger car sub-use cases

Passenger car sub-use cases	Description
Road use pricing	**Static city toll**: A fixed fee is applied to all vehicles entering the city centre. **Dynamic city toll**: A dynamic fee is applied to all vehicles inside the city centre (depending on area, traffic load and time of day).
Parking behaviour (parking price)	A fee is applied to all vehicles parking inside the city centre.
Parking space regulation	Parking space regulation comprises five sub-scenarios (sub-sub-use cases): • Replace on-street parking space with space for public use: On-street parking inside city centre is reduced by the designated rate, and the space previously used for parking is transformed to sidewalks, planted areas, etc. • Replace on-street parking space with cycling lanes: On-street parking inside city centre is converted to dedicated cycle lane. • Replace on-street parking space with driving lanes: On-street parking inside city centre is reduced by the designated rate, and the space previously used for parking is transformed to additional driving lanes. • Replace on-street parking space with 'pick up / drop off': On-street parking inside city centre is reduced by the designated rate and transformed to 'pickup/drop off' parking space. • Remove half of the on-street parking space in the city centre.
Dedicated lanes	Provision of dedicated lanes for AVs on urban highways.
GLOSA	Providing green light optimised signal advisory to connected cars.
Automated ride sharing	Enabling of automated ride sharing in passenger cars.

Sources: Haouari et al. (2021), Sha et al. (2021), Chaudry et al. (2021).

Road-use pricing - static city toll on vehicles entering the city centre

Firstly, regarding implementation costs, for this road-use pricing scenario, the costs (start-up and operation) might probably vary with respect to the number of installations (e.g., sensors), if such equipment is needed for counting passing (entering) vehicles.

Regarding monetised impacts (and positive/negative benefits), as indicated above, the behavioural response to fees and other policy is taken as given in the CBA module. The particular information from the PST that is applied in the CBA module related to static toll, on all vehicles entering the city centre, comprises:

- ✓ the size of the static toll (fee), in the policy scenario, via the user selection in the PST; the user can select from an interval of fees (from €5 via €10 to 100€ per entrance, set according to the EU-28 GDP/capita average of 30,500 EUR_{2020}); and
- ✓ the number of entries of (toll-paying) vehicles into the city centre, in the policy scenario and in the reference scenario; we summarise below an approach to deriving the no. of entries, applying various PST variables.

The size of the static toll ($p_{\text{fee\_static}}$) will potentially affect all car users' consumer surplus; it will increase their generalised costs (if they enter the city centre). The collected fee will constitute an income for the policy entity.

In the PST for road-use pricing SUCs, the following impacts are not included: delay/congestion, crashes beyond injury crashes with active travellers (VRU), and emissions. In these cases, we derive the needed variables, but fixed values over time and similar inputs for baseline and policy case will imply relatively limited impacts on the CBA result.

Road-use pricing - dynamic city toll on vehicles travelling in the city centre

Regarding implementation costs, for this road-use pricing scenario, the costs (start-up and operation) will probably vary with respect to the number of installations (e.g., sensors), if such equipment is needed for tracking vehicles within the city centre.

Regarding monetised impacts, the information from the PST that is applied in the CBA module related to dynamic toll, on all vehicles entering the city centre, comprises:

- ✓ the average size of the dynamic fee, in the policy scenario, via the user selection in the PST; the user can select from an interval of fees (from €5/7=€0.7 via €10/7=€1.4 to €100/7=14 per km, set according to the EU-28 GDP/capita average of 30,500 EUR_{2020}; the 7 referring to the assumed 7 km as the average travel length within the city centre yielding parallel price levels as for the static fee); and
- ✓ the quantity of driving (vkm) within the city centre (by toll-paying vehicles), in the policy scenario and in the reference scenario; we summarise below an approach to deriving the kms by cars in the city centre, applying various PST variables plus the assumption of 7 km as average driving length within the centre (Sha et al. 2021).

The size of the fee ($p_{\text{fee\_dynamic}} = p_{\text{fee\_static}}/7$) will potentially affect all car users' consumer surplus; it will increase their generalised costs (if they enter the city centre). The collected fee will constitute an income for the policy entity.

As stated above, to ensure CBA module functionality, we derive some variable proxies that are omitted in the PST for road-use pricing SUCs: delay/congestion, crashes beyond injury crashes with active travellers (VRU), and emissions.

Road-use pricing – empty km pricing in the city centre
Empty km pricing is similar to the dynamic city toll but applies only to automated cars that drive empty in (Haouari et al. 2021). Somewhat similarly to the dynamic fee described, there would be need for some tracking system in the city centre, either via the cars' GPS (corresponding to a generalised technology for road-use pricing) or via installations along the roads. There is an additional complexity in registering (zero) occupancy compared to registering only the car itself.

Regarding monetised impacts, the information from the PST that would be applied (on the benefit side) in the CBA module related to (dynamic) empty km pricing, of automated vehicles inside the city centre, would comprise:

- ✓ the average size of the dynamic fee, in the policy scenario, via the user selection in the PST; the user can select from the same interval of fees as for dynamic toll; and
- ✓ the quantity of empty km driving (vkm) within the city centre by automated cars, in the policy scenario and in the reference scenario; we summarise below an approach to deriving the kms by automated empty cars.

The average size of the fee ($p_{\text{fee\_empty}}$) will potentially affect the automated car users' consumer surplus; it will increase their generalised costs, if they send or have delivered their automated car empty, within the city centre. (We refer to "users" of automated cars, although in some cases the owners (those paying the operation costs and fees) might not be the actual users.) The collected fee will constitute an income for the policy entity.

Parking behaviour in the city centre
Firstly, the parking-price / parking-behaviour sub-use case can be specified for different combinations of behavioural response to a parking fee. These specified behavioural responses comprise, in addition to "park in centre and pay fee" (reference behaviour): "drop-off passengers in centre and returning to origin", "drop-off passengers in centre and returning to parking outside the centre", and "driving around in the centre". The distribution of these provide three scenarios: "balanced" (with behaviours distributed across all behaviour, including parking in centre and paying fee), "heavy return to origin and park outside" (no parking in centre and no driving around), and "drive around" (Haouari et al. 2021). The behaviour will yield monetised impacts via PST variables, even if the parking fee is set equal for the reference as for the three sub-use case behavioural alternatives.

The parking behaviour sub-use case does not readily fit into the standard CBA policy measure vs. a "do nothing" reference. A policy, a parking fee, is already implemented, also for the reference, thus the sub-use case compares behavioural responses. Although a delineation similar to the road-use pricing SUCs would fit better in CBA, we might still compare alternatives, bearing in mind the indicated limitation. It follows that implementation costs for the policy scenarios lose relevance, if the implementation costs are the same for the reference (as the reference in this SUC is *not* "do nothing"). Possibly we might consider this SUC as a monitoring measure; and, e.g., the cost of implementation might comprise installation of sensors.

Regarding monetised impacts beyond those already handled by monetised PST variables, we can add the approximate underlying parking fee ($p_{\text{fee\_parking}}$) and include it in transfers and generalised costs for the different simulated behaviours; that also comprises the fee collection of the policy entity. The parking fee is a fixed underlying fee (set to 3€ per hour, or 0.50€ per 10 minutes, in the CBA module) that drives the alternative simulated behavioural responses. Thus, the parking fee is not adjustable, neither in the PST in general nor in the CBA module; the parking fee is only applied for calculating monetised impacts for the car drivers and the policy entity.

For the baseline "park in centre and pay fee", 100% of the automated (and manual) vehicles entering the centre are assumed to park and pay the fee. For "drop-off passengers in centre and returning to origin", "drop-off passengers in centre and returning to parking outside the centre", and "driving around in the centre", 0% of automated cars are assumed to park and pay fee. In the case of a "balanced" scenario, 13% of automated cars are assumed to park and pay (Haouari et al. 2021, Table 3.3, p. 24). We assume, implicitly, that manual car drivers are not varying their behaviour, they park and pay in all cases. Furthermore, we assume an average parking duration of 4 hours (Bates & Leibling 2012).

We summarise below an approach for deriving the no. of cars parked (per day), applying various PST variables. The parking fee will potentially affect car users' consumer surplus, via the generalised costs, if the extent of parking differs between policy and baseline. If so, also the collected parking fee, the income for the policy entity, will differ.[67]

Replace on-street parking space

As indicated, this sub-use case has five specified scenarios: i) replacing on-street parking spaces with public spaces, ii) replacing on-street parking spaces with cycling lanes, iii) replacing on-street parking spaces with driving lanes, iv) replacing on-street parking spaces with pick-up and/or drop-off points; and v) removing half of the on-street parking spaces (Haouari et al. 2021). The selected combination might have an impact on both implementation costs and monetised impacts of the sub-use case.

Regarding implementation costs, the costs (start-up and operation) will probably vary with respect to the size of the replaced area. This might include variations in re-construction work and amounts of new installations.

Regarding monetised impacts, replacing on-street parking space with specified new utilization is supposedly based on an anticipation of reduced (more efficient) parking due to automation.

The information from the PST that is applied in the CBA module related to replacing on-street parking space, comprises:

- ✓ the percentage of parking space transformed in the policy scenario (for i), conversion to public space; a default value in the PST is set within the interval of 25%-75% of total parking space in the city centre and we apply 50% as default in our CBA; for ii)

[67] The required parking space (m^2/person) in the city centre, from the PST, is provided for all use cases.

and iii), conversion to either cycle lane or driving lane for motorised transport, a default value in the PST is set within the interval of 10%-35% of total parking space in the city centre and we apply 20% as default in our CBA; for iv), conversion to space for 'pick up / drop off', a default value in the PST is set within the interval of 10%-35% of total parking space in the city centre and we apply 20% as default in our CBA; and for v) a fixed 50% removal of parking space is set).

For conversion of parking lots to public space (i), the size of the parking space reduction ($A_{\text{park\_replace\_sqm}}$) is applied together with an average square metre value ($p_{\text{land\_sqm}}$), in the CBA. As a default we apply an average square metre value for "undeveloped" land in the centric areas of the city that has a potential for "development" (300€ per m^2 for GDP/capita equal to 30,500 EUR$_{2020}$).[68] For conversion to cycling lanes or driving lanes or pick-up and/or drop-off points, there is no released space for other utilization that we could value by an average square metre value; then the impact is only traced via other changes in PST variables.

Dedicated lanes for AVs

Firstly, this sub-use case is specified for four different combinations of road types: motorway only, motorway and trunk road ("A road"), A road only – rightmost lane, A road only – leftmost lane. The selected specification might have an impact on both implementation costs and monetised impacts of the sub-use case.

Regarding implementation costs (start-up and operation), these will probably vary with respect to the extension of the lanes to be transferred to AVs. In addition, there are initial planning/preparation costs, as for all sub-use cases.

Regarding the monetised impacts, there is no particular information from the PST that we emphasize for the CBA related to this sub-use case. There are various potential impacts of the policy scenario that can be monetised, impacts on generalised costs and subsequently the consumer surplus changes, e.g., via travel time averages and congestion.[69] We assume that the dedicated lane is to be a repurposing of an existing lane, not construction of new lanes.

Green-light-optimised signal advisory (GLOSA)

Firstly, this sub-use case has three different specifications, three levels of GLOSA provision ("on 1 intersection", "on 2 intersections", and "on 3 intersections") that might have an impact on both implementation costs and monetised impacts of the sub-use case.

[68] A policy project that envisage a transformation of the space previously used for parking to "sidewalks, planted areas, etc." will represent a development of the space that can increase its average square metre value (relative to "undeveloped"). There is however a challenge in obtaining more or less generic "unit values" for the described alternative utilizations of public space.

[69] Dedicated lane will be mandatory for automated vehicles and public transport; the AVs are then not allowed to travel in other lanes and manual vehicles (not public transport) are not allowed to travel in the dedicated lanes for AVs. Provision of dedicated lanes for AVs on urban highways resemble existing policies of dedicated lanes for public transport and taxis, that also comprise electric vehicles in Norway. In an introductory phase of a vehicle type, dedicated lanes will supposedly imply lower congestion levels for those vehicles.

Regarding implementation costs (start-up and operation), these will probably vary with respect to the extension of the provision of GLOSA. In addition, there are initial planning/preparation costs, as for all sub-use cases.

Regarding the monetised impacts, also for the sub-use case of providing GLOSA to automated and connected cars, we assume that all impacts of this policy scenario are handled in the "general framework" of the CBA. One might, e.g., expect changes (reductions) in travel time averages and congestion, affecting consumer surpluses.

Automated ride sharing
Firstly, this sub-use case has various combinations of the share of demand served (5, 10, or 20%) and the willingness to share (20, 50, 80, or 100%), 12 combinations in total. The combination of demand served and willingness to share might have an impact on both implementation costs and monetised impacts of the sub-use case.

Regarding implementation costs, the costs (start-up and operation) might possibly vary with respect to a quantity of 'pick up / drop off' parking lots dedicated to automated ride sharing vehicles, if establishing such lots is part of the policy implementation.

Regarding monetised impacts, this sub-use case considers a type of automated ride sharing that can be termed "shared automated taxis".[70] As a paid service, automated ride sharing will be like existing (manual) shared taxis, as well as resembling automated on-demand services under AUSS sub-use cases (see above).

We present, in a table below, the particular elements that are applied in the CBA calculation, which has more or less the same structure as for on-demand AUSS.

Summarising a common approach to deriving particular input to CBA of road-use pricing, parking behaviour, parking space replacement, and automated ride sharing
The following procedure is followed for deriving no. of car entries to the city centre for static toll, dynamic toll and parking behaviour; for dynamic toll there is an additional assumption of 7 km distance driven within the city centre and the fee per km is one seventh of the static toll per entry:
The point of departure is the amount of travel (pkm) and modal split variables from the PST, plus the occupancy rate (in cars) and the average (round-trip) commuting distance (that is divided by two, to yield an estimate of average trip length).

- The amount of travel, the sum of pkm in PST (Q) is assumed to comprise the travel activity that either involves destinations in the city centre or destinations beyond whereby passing through the centre is relevant; the pkm by car is a residual: $\left(1-\left(s_{\text{pkm\_public}}+s_{\text{pkm\_active}}\right)\right)*Q=s_{\text{pkm\_car}}*Q=Q_{\text{car}}$.
- Total vkm by car, $T_{\text{car}}=Q_{\text{car}}/n_{\text{occ\_car}}$, can be divided by average trip length ($\bar{T}_{\text{trip}}$) to produce an estimate of the no. of entries by car to the city centre, the figure

[70] App-based manual taxi services with shared rides exist already. This sub-use case does not comprise private "2+ ride share" where privately-owned cars could be shared via ride-sharing web / apps. The PST does include a variable on *shared mobility rate* "the percentage of trips made sharing a vehicle with others" (with an initial default at 4%). This variable refers to shared vehicle ownership with persons from other households (car clubs), as well as shared trips with persons from other households. It does not comprise "ordinary" (non-sharing) use of taxies, nor ordinary car rental.

we seek for calculating static fee payments and collection; which is also applied in the calculation of parking fee payment.

- Dividing the no. of entries by the assumed trip distance within the centre ($\bar{T}_{\text{trip\_centre}} = 7$), yields the kilometres by car inside the city centre, which is the figure we seek for calculating dynamic fee payments and collection; while the remaining of average trip distance minus 7 km occurs outside the centre ($\bar{T}_{\text{trip\_notcentre}} = \bar{T}_{\text{trip}} - \bar{T}_{\text{trip\_centre}}$).
- We have no information from the PST on the shares of empty car driving within the city centre with and without the fee. Hence, we apply a very simplistic approach of testing the impact of just halving the share; from 20% without fee to 10% with a fee. These shares are not resulting from models; we only know that there is an effect of fees, but we might very well overestimate the effect of a €0.7/km fee and underestimate that of €14/km. However, we include the functionality in the CBA module (and allows the PST/CBA to adjust the expected impact of the selected fee level).
- For parking fee payment, we apply the same estimate of no. of entries by car to the city centre as for the static fee ($T_{\text{car}}/\bar{T}_{\text{trip}}$). This number is multiplied by the parking duration per car, in hours ($\bar{h}_{\text{hour\_parking}}$), which is multiplied by the parking fee per hour ($\bar{p}_{\text{fee\_parking}}$); which yields the figure we seek for calculating parking fee payments and collection.
- For parking space change, we multiply the PST variable *parking space* ($\bar{a}_{\text{pop\_parking\_sqm}}$) by the PST variable *city population* (POP), yielding an estimate of the city centre parking space in m^2, ($A_{\text{parking\_sqm}}$); and that area estimate is multiplied by the square metre value ($p_{\text{land\_sqm}}$).[71]

These additional calculations for road-use pricing, parking behaviour, and parking space replacement will produce inputs to generalised travel costs of car drivers (fee payment) and policy entity income (fee collection); needed inputs to the CBA that cannot be obtained directly from the PST.

[71] Due to scale variations, multiplying the square metres demanded per person by the PST variable *city population* (POP), will potentially yield large area estimates and then potentially large changes between scenarios that will dominate among monetised impacts. If this were an unintended artefact, two approaches could be envisaged: either i) introducing an additional population variable in the CBA module, say the share of the city population affected by the policy implementation ($\bar{a}_{\text{pop\_parking\_sqm}} * \text{POP} * \%\text{POP}$, where $\%\text{POP}$ is an estimated percentage of the population affected by the policy measure); or ii) applying the travel information from PST variables to derive an estimate of total city centre parking space, e.g., multiplying the no. of entries ($T_{\text{\_car}}/\bar{T}_{\text{trip}}$) by the PST variable *parking space* ($\bar{a}_{\text{pop\_parking\_sqm}}$) to estimate city centre parking space.

Table 2.28 summarises the additional sub-use-specific input that we apply for the 12 combinations of automated ride sharing (Haouari et al. 2021), in addition to standard PST input (and "wts" refers to "willingness to share"). We can apply this input to derive more CBA-relevant figures, as shown in

Table 2.29.

Table 2.28: Particular input to CBA of automated ride sharing under passenger car sub-use cases

Demand to be served	General assumptions / inputs							
	trips served	fleet size	seat capa-city	replace-ment rate	occu-pancy (not empty)	fleet trip distance (km)	fleet empty-vehicle distance (km)	share empty
5%								
20% wts	1134	645	*5*	*1.8*	*2.3*	*5800*	*2800*	*48.0%*
50% wts		570	*5*	*2.0*	*2.5*	*5400*	*2500*	*46.0%*
80% wts		490	*5*	*2.3*	*2.9*	*4900*	*1900*	*39.0%*
100% wts		435	*5*	*2.6*	*3.3*	*4500*	*1600*	*36.0%*
10%								
20% wts	2239	1154	*5*	*1.9*	*2.4*	*11,100*	*5200*	*47.0%*
50% wts		1009	*5*	*2.2*	*2.8*	*10,000*	*4400*	*44.0%*
80% wts		839	*5*	*2.7*	*3.4*	*9,100*	*3500*	*38.0%*
100% wts		720	*5*	*3.1*	*3.9*	*8,200*	*2800*	*34.0%*
20%								
20% wts	5070	2391	*5*	*2.1*	*2.6*	*24,800*	*11,100*	*45.0%*
50% wts		2067	*5*	*2.5*	*3.1*	*22,100*	*9200*	*42.0%*
80% wts		1694	*5*	*3.0*	*3.8*	*19,500*	*7000*	*36.0%*
100% wts		1436	*5*	*3.5*	*4.4*	*17,600*	*5200*	*30.0%*

Sources: Haouari et al. (2021, Table 3.4, Figure 3.13), Demo-SUC-spreadsheet.

The figures in

Table 2.28 and

Table 2.29 can be applied for estimating costs for the automated shared taxi providers as well as generalised costs for the passengers. We propose the following scaling of the SUC applying PST variables: The PST variable *amount of travel* is applied for deriving overall passenger car pkm and, by use of the occupancy, passenger car vkm. Fixed scaling parameters and other table content are then applied for deriving the scale of the automated ride sharing; and these are: $\alpha_{\text{auttaxi\_5\%\_20\%}} = 15.2\%$, $\alpha_{\text{auttaxi\_5\%\_50\%}} = 14.0\%$, $\alpha_{\text{auttaxi\_5\%\_80\%}} = 12.0\%$, $\alpha_{\text{auttaxi\_5\%\_100\%}} = 10.8\%$, $\alpha_{\text{auttaxi\_10\%\_20\%}} = 28.8\%$, $\alpha_{\text{auttaxi\_10\%\_50\%}} = 25.5\%$, $\alpha_{\text{auttaxi\_10\%\_80\%}} = 22.3\%$, $\alpha_{\text{auttaxi\_10\%\_100\%}} = 19.5\%$, $\alpha_{\text{auttaxi\_20\%\_20\%}} = 63.5\%$, $\alpha_{\text{auttaxi\_20\%\_50\%}} = 55.4\%$, $\alpha_{\text{auttaxi\_20\%\_80\%}} = 46.9\%$, $\alpha_{\text{auttaxi\_20\%\_100\%}} = 40.3\%$.

Table 2.29: Derived input to CBA of automated ride sharing under passenger car sub-use cases

Demand to be served	Derived figures					PST scale	
	occupancy (weighted)	daily fleet vkm	daily fleet pkm	daily pass. no.	average trip dist.	daily amount of travel (km)	% shared-ride fleet km
5%							
20% wts	*1,5*	*8 600*	*12 900*	*2 552*	*5,1*	*56 545,82*	*15,20%*
50% wts	*1,7*	*7 900*	*13 430*	*2 835*	*4,7*	*56 545,82*	*14,00%*
80% wts	*2,1*	*6 800*	*14 280*	*3 260*	*4,4*	*56 545,82*	*12,00%*
100% wts	*2,4*	*6 100*	*14 640*	*3 686*	*4,0*	*56 545,82*	*10,80%*
10%							
20% wts	*1,6*	*16 300*	*26 080*	*5 318*	*4,9*	*56 545,82*	*28,80%*
50% wts	*1,9*	*14 400*	*27 360*	*6 157*	*4,4*	*56 545,82*	*25,50%*
80% wts	*2,4*	*12 600*	*30 240*	*7 557*	*4,0*	*56 545,82*	*22,30%*
100% wts	*2,9*	*11 000*	*31 900*	*8 676*	*3,7*	*56 545,82*	*19,50%*
20%							
20% wts	*1,8*	*35 900*	*64 620*	*13 309*	*4,9*	*56 545,82*	*63,50%*
50% wts	*2,2*	*31 300*	*68 860*	*15 844*	*4,3*	*56 545,82*	*55,40%*
80% wts	*2,8*	*26 500*	*74 200*	*19 013*	*3,9*	*56 545,82*	*46,90%*
100% wts	*3,4*	*22 800*	*77 520*	*22 181*	*3,5*	*56 545,82*	*40,30%*

At the time of writing the deliverable, we have no default figures for the costs of implementing the passenger car sub-use cases; the costs of planning/preparing a project plus costs of installations and their management (beyond vehicle operating and ownership costs). In the CBA module we will set a (fixed) default of €1 million in start-up costs and €10,000 in annual operation costs (for GDP/capita equal to 30,500 EUR_{2020}).

Freight and logistics use case

The freight transport scenarios differ considerably from the passenger transport scenarios. Primarily, the for the freight transport use case the PST does not report travel distances, neither for freight nor for passenger transport. We specify below how we propose that CBA can handle such confines. The freight and logistics sub-use cases (Hu et al. 2021a, b, c) are listed in Table 2.30.

Table 2.30: Freight and logistics sub-use cases

Freight and logistics sub-use cases	Description
Automated urban freight delivery	Automated urban freight delivery includes three sub-scenarios (sub-sub-use cases): semi-automated delivery, automated delivery, and automated night delivery: • 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. • Automated delivery assumes that automated vans (robo-vans) and small autonomous delivery robots replace all service personnel and operate beyond the road (pavement, pedestrian area, etc.); the automated van functions as a mobile hub for short delivery trips to end-customers, i.e., a hub-and-spoke setup with moving hubs. • Automated night delivery extends the previous scenario and applies night delivery only.
Automated local freight consolidation	Automated local freight consolidation includes two (additional) sub-scenarios (sub-sub-use cases): manual delivery with bundling at city hubs, and automated delivery with bundling at city hubs: • Manual delivery with bundling at 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 combines the automated delivery via robo-vans and the city-hubs for bundling.
Hub-to-hub automated transfer	Introduction of truck terminals where long-range freight containers are passed to automated trucks, which operate the long-haul highway segments without drivers.

Sources: Hu et al. (2021a, b, c).

<u>Automated urban freight delivery</u>

First of all, this sub-use case comprises three alternative policy scenarios: i) semi-automated delivery, ii) full-automated delivery, and iii) full-automated delivery with night shifts only. With respect to the reference, manual delivery, Hu et al. (2012b) assess that the semi-automated delivery (i) will save time during each stop, because the use of an automated delivery van will imply that no switch is needed between delivery (which is manual) and driving (which is automated). The automated delivery (ii) comprises delivery both during daytime and during the night – fully automated delivery processes can be carried out at night and during off-peak hours. The scenario involving automated delivery at night only (iii) will require larger fleet size to accomplish total delivery in less shifts (Hu et al. 2021a, b).

Regarding implementation costs, one could assume some minor start-up costs due to planning/preparation. Notwithstanding, implementation costs are supposedly very limited (or close to zero) if the automation of delivery is primarily a vehicle replacement.

Regarding the change of freight vehicles, from manual to semi-automated or automated, we place these as monetised impacts (change in operation and ownership costs) on the “benefit side” in the CBA. Beyond the freight transport cost from PST, which we assume applies to the specified type of LCV (delivery vans), we establish a CBA framework utilising the input from Hu et al. (2021a, b). That input comprises primarily the vkm estimates for the fleet of freight vehicles under the baseline and alternative policy scenarios. We specify below the proposed CBA approach.

Automated freight consolidation

This sub-use case adds automated freight consolidation/re-stocking at hubs/terminals to either a manual delivery or an automated delivery; the reference remains the same as for automated urban freight delivery, that is, manual delivery. Thus, the sub-use case comprises two alternative policy scenarios: i) manual delivery with bundling at city hubs, where the servicing of city-hubs and the delivery to end-customers are done manually; and ii) automated delivery with bundling at city hubs; the delivery is done during day and night, whereas the transport from distribution centres to city hubs is done during the night (Hu et al. 2021a, b).

Regarding implementation costs, there are start-up costs (initial investment costs) for building the hubs, and possibly some operation costs. We apply EUR_{2020}500,000 per hub as start-up costs, according to the EU-28 GDP/capita average of 30,500 EUR_{2020}; this investment cost does not include land costs.[72] Possibly one could also imagine other planning/preparation (and fieldwork) related to the freight consolidation. The start-up cost is assumed to vary with *city population*; with 8 hubs per million inhabitants.

Regarding the change of freight vehicles (from manual to automated), we place these as monetised impacts (operation and ownership costs) on the "benefit side" in the CBA.

Beyond the freight transport cost from PST, which we assume applies to the specified type of LCV (delivery vans), we establish a CBA framework utilising the input from Hu et al. (2021a, b). That input comprises primarily the vkm estimates for the fleet of freight vehicles under the baseline and alternative policy scenarios. The consolidation will also involve freight by HGV. We specify below the proposed CBA approach.

Hub-to-hub automated transfer

This sub-use case applies to trucks (HGVs) only. While the baseline involves "manual container trucks ... operating between their origin and destinations" (Hu et al. 2021b, p. 10), the policy scenario implies building transfer hubs and inclusion of automated HGVs. There will be a mix of automated and manual HGVs in the hub-to-hub policy implementation.

Regarding implementation costs, there are start-up costs (initial investment costs) for building the hubs, possibly also operation costs. As for consolidation, we apply EUR_{2020}500,000 per hub as default start-up costs (not including land costs). One could imagine other planning/preparation (and fieldwork) costs. The start-up cost is assumed to vary with *city population*; with 2 hubs per million inhabitants.

Less CBA-relevant input is available for the hub-to-hub sub-use case. However, we establish a framework utilising the input from Hu et al. (2021b, c), as well as additional information from the underlying micro simulations. The latter provides vkm estimates for the fleet of freight vehicles under the baseline and alternative policy scenarios. We will also need to delineate the geographical reach, the extent of the PST-based impacts that are within the city area and what is inter-city activities (e.g., most of the long-haul freight transport). We specify below the proposed CBA approach.

[72] Pers. comm. Hu Bin.

Summarising particular input to CBA approach for freight and logistics sub-use cases
For automated delivery and automated consolidation, the inputs (assumptions) are based on Table 4.1 and Table 4.3 in Hu et al. (2021a, p. 20 & p. 23). For the hub-to-hub sub-use case, the input is based on partly on Hu et al. (2021c, p. 10) and partly on the underlying micro simulation of the sub-use case (the vkm). The following table summarises freight-sub-use-specific input for the CBA, primarily LCV-related input from Hu et al. (2021a, b). All monetised figures represent levels according to the EU-28 GDP/capita average of 30,500 EUR_{2020}.

Table 2.31: Particular input to CBA of sub-use cases under freight transport scenarios

Freight SUC	**Assumptions - automated delivery / manual/automated consolidation (LCV)**					**→ LCV - average daily driven vkm, fleet of van**	**HGV - average daily bundle-trip vkm by truck**	**→ LCV+HGV - average daily driven vkm**
	Fleet size	**No. of tours**	**Tour length, km**	**Annual costs per vehicle**	**Annual fleet costs**			
Manual delivery	*1799*	*1799*	*44,7*	*€53,500*	*€96,246,500*	*80,389*		***80,389***
Semi-automated delivery	*1440*	*1440*	*49,2*	*€53,280*	*€76,723,200*	*70,805*		*70,805*
Automated delivery	*898*	*2692*	*39,4*	*€33,500*	*€30,083,000*	*106,177*		*106,177*
Automated night delivery	*1795*	*2692*	*39,4*	*€33,500*	*€60,132,500*	*106,177*		*106,177*
Manual delivery	*1799*	*1799*	*44,7*	*€53,500*	*€96,246,500*	*80,389*		*80,389*
Manual delivery with city-hubs	*1806*	*1806*	*13,7*	*€53,500*	*€96,621,000*	*24,675*	*10,445*	*35,120*
Automated delivery with city-hubs	*906*	*2716*	*11,9*	*€33,500*	*€30,351,000*	*32,347*	*10,445*	*42,792*
Manual origin-destination							*109,499*	*109,499*
Automated hub-to-hub							*109,499*	*109,499*

Sources: Hu et al. (2021a, b), Demo-SUC-spreadsheet.

The daily total of vkm for the included freight vehicles can be multiplied by 312 (annual operating days) to yield annual vkm (thus, e.g.: $T_{\text{freightSUC\_manLCV}} = 80{,}389 * 312$). This is the vkm for the initial year (2020), which is assumed to grow over time with the population growth. This applies to all freight sub-use cases.

The figures in Table 2.31 are assumed to represent the levels in a city of 2 million inhabitants; the fleet size and subsequent freight activity, and vkm, will be scaled by use of the PST variable *city population*. For consolidation it is assumed a need for 8 hubs per million inhabitants, while for hub-to-hub there will be 2 hubs per million inhabitants. Thus the scaling parametre for the default values in Table 2.31 as well as Table 2.32 (below) is: $\alpha_{\text{freight}} = \text{POP}/2{,}000{,}000$.

Table 2.32: More derived input to CBA of sub-use cases under freight transport scenarios

Freight SUC	→ LCV - voc per vkm - assumed voc for HGV	average load (tonne)	→ freight transport costs per tkm	→ LCV - average annual vkm per vehicle	HGV - assumed average annual vkm per vehicle	→ derived for HGV annual fleet costs	annual cost per vehicle	fleet size
Manual delivery	*€3.84*	*0.2075*	*€18.50*	*13,942*				
Semi-automated delivery	*€3.49*	*0.2365*	*€14.80*	*15,341*				
Automated delivery	*€0.92*	*0.1324*	*€6.90*	*36,890*				
Automated night delivery	*€1.84*	*0.1407*	*€13.10*	*18,455*				
Manual delivery	*€3.84*	*0.2075*	*€18.50*	*13,942*				
Manual delivery with city-hubs	*€12.55 / €2.98*	*0.2049 / 1.9*	*€61.20 / €1.60*	*4263*	*25,000*	*€41 mill.*	*€74,400*	*551*
Automated delivery with city-hubs	*€3.05 / €1.21*	*0.1384 / 1.2*	*€21.70 / €1.00*	*11,139*	*35,000*	*€10 mill.*	*€40,900*	*244*
Manual origin-destination	*€2.98*	*1.9*	*€1.60*		*25,000*	*€102 mill.*	*€74,400*	*1371*
Automated hub-to-hub	*€2.08*	*1.6*	*€1.30*		*30,000*	*€71 mill.*	*€57,650*	*1232*

The voc level for automated delivery is lower in Table 2.32 compared to the levels shown in

Table 2.13, Table 2.14, and Table 2.15; it is calculated from annual costs in Hu et al. (2021a, Table 4.3), a top-down instead of bottom-up calculation; beyond that the differences are due to rounding errors.

For the purpose of attaching monetised impacts (congestion, road safety, emissions) to vkm of transport modes, we estimate the remaining freight activity in the given area from the manual delivery baseline. That is:

$$T_{\text{freightNONSUC}} = T_{\text{freightSUC\_manLCV}} * 9$$

This implies that we assume the delivery van vkm to represent 20% of all freight vkm in the area.[73] This relationship, to invoke non-SUC freight, is applied to all SUC-freight. There will be a slight variation in vkm across chosen sub-use cases, between baseline and policy alternatives; e.g.:

$$T_{\text{freight}}^{\text{SUC\_man\_del}} = T_{\text{freightSUC\_manLCV}} + T_{\text{freight\_NONSUC}} \neq T_{\text{freight}}^{\text{SUCaut}_{\text{del}}} = T_{\text{freightSUC\_autLCV}} + T_{\text{freigh\_NONSUC}}$$

However, as $T_{\text{freight\_NONSUC}}$ is based only on $T_{\text{freightSUC\_manLCV}}$, it will remain stable between baseline and policy scenario, for all sub-use cases (and stable between SUCs).

Indeed, we apply the same relationship for deriving non-SUC freight in the hub-to-hub sub-use case. This sub-use case involves only HGV (trucks) and has a somewhat different localisation in the city area. Actually, in case of the hub-to-hub, we assume no difference between SUC-freight distance in the baseline and the policy.

As shown above, in section 2.2.2, we estimate passenger transport vkm by, e.g., for automated consolidation, as:

$$T_{\text{passenger}} = \left(T_{\text{freightSUC\_manLCV}} + T_{\text{freight\_NONSUC}}\right) * 9$$

So, $T_{\text{passenger}}$, the vkm distance in passenger transport, will not fluctuate artificially due to differences between baseline and policy (e.g., due to the vkm difference between $T_{\text{freightSUC\_manLCV}}$ and $T_{\text{freightSUC\_autLCV}}$). Then, using default occupancies and default pkm modal shares, we can derive vkm modal shares and estimate vkm and pkm for each passenger transport mode.

For consolidation and hub-to-hub HGV, we lack the type of input specified for LCV in the table above. However, if we apply the input from Table 2.11 and Table 2.15, together with Table 2.31, we can derive parallel estimates for HGV. Table 2.32 summarises the derived estimates (where money values represent GDP/capita equal to 30,500 EUR_{2020}).

For consolidation (delivery with city hubs), voc estimates for both LCV (leftmost) and HGV (rightmost) are included. For automated hub-to-hub, there is a mix of automated and manual HGV (trucks); as a default we apply a 50% vkm share of each, yielding weighted averages of voc per vkm.

[73] A study from Vienna found that parcel (delivery) transport represented 0.8% of all trips on the roads in the city, while freight trips in total constituted 13.5% of all trips (https://www.verkehr.co.at/singleview/article/paketlogistik-am-gesamtverkehr-nur-08, retrieved 19th of March 2022. The parcel transport would then represent about 6% of all freight trips. Due to relatively longer mileage per trip in parcel transport, we set the share of vkm to 20% (Hu Bin, pers. comm.).

For HGV, annual fleet costs are derived as the annual fleet mileage (vkm) times the voc; annual costs per vehicle are annual vkm per vehicle times the voc; and the fleet size is derived from the fleet cost divided by the vehicle cost.

What is provided from PST under freight transport scenarios is the *freight transport cost*, the "direct outlays for transporting a tonne of goods per kilometre of travel". We consider that this is a general figure that does not apply to a specific type of freight vehicle. The CBA module calculates monetised impacts per vkm, and we apply directly the voc for the different freight vehicles, in Table 2.32 (from Hu et al. 2021a). However, we apply the growth in the PST variable *freight transport cost* to setting the growth of the voc for all freight vehicles and weighted averages of voc.[74]

As indicated above, the freight transport SUCs, more precisely the costs of implementation and the freight vkm, are scaled with respect to *city population*; the figures presented above are based on a *city population* of 2 million.

[74] We have disregarded the SUC about platooning on urban highway bridges, as we lack necessary input for CBA of that SUC (Hu et al. 2021b).

3 CBA – calculations

This chapter describes how the CBA (the monetised impacts, the "benefit side") is carried out for different "agents", i.e., the transport consumers and the transport service providers (infrastructure users), the communities (external effects beyond those on other infrastructure users), and the policy entity.

The main agents in the CBA are shown in Figure 3.1, also including main categories of calculations (of changes in monetised impacts):

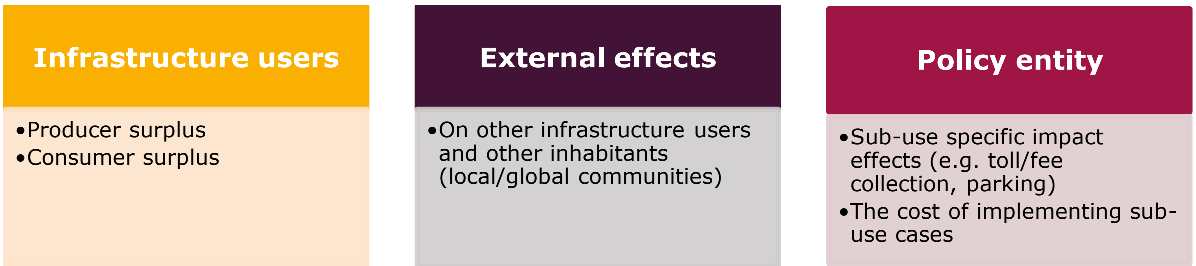

Figure 3.1: Agents in the CBA and calculations of changes in monetised impacts

In the following sub-chapters, we present the specific calculations of the monetised impacts, under the main agents.

3.1 The change from baseline to policy in money terms

The CBA module will have a common framework of functionalities for all sub-use cases, allowing for calculations of monetised impacts on all infrastructure users, plus external effects and the impacts for the entity that implements policy, fee collection in some sub-use cases and policy implementation costs.

The infrastructure users comprise:
- transport consumers (passengers of shuttles / public transport and passenger cars, as well as active transport users); and
- transport service providers (shuttles / public transport, ride-sharing taxis, and freight service providers).

For the transport service providers, simplistic producer surplus changes will be estimated; and for transport consumers, the consumer surplus changes will be estimated (Boardman et al. 2018; Mishan & Quah 2020; de Rus & Johansson 2019). The main driver of changes in these measures will be the changes in travel time and/or operating costs (the "internal costs" for the transport service providers/users).

The external effects comprise impacts that infrastructure users inflict upon themselves and upon others. We include emissions of local pollutants and climate gas, the external cost of crashes, and external congestion costs.

3.2 Consumer surplus changes for transport users

3.2.1 The rule-of-the-half

A measure of the change in generalised costs for each transport mode
The handling of impacts on transport consumers will be based on estimated consumer surplus changes. The public transport passengers, car occupants, and active travellers, reveal a demand (or willingness-to-pay) for transport (or the activities that transport enables). We will not be able to estimate demand or willingness-to-pay for the elements of the sub-use cases, but we will estimate a *change* in consumer surplus (ΔCS) that the policy implementations bring about.

The consumer surplus change is estimated by use of the "rule-of-half" formula. Applied to a change in generalised costs (GC), primarily travel time and operation costs, with an expected subsequent change in travel quantity (Q), the rule-of-a-half (or rule-of-a-half, or rule-of-the-half) depicts that half the product of cost change times travel quantity change represents the change in consumer surplus that follows from the travel quantity change (Boardman et al. 2018; Mishan & Quah 2020; de Rus & Johansson 2019):

$$\Delta CS = \frac{1}{2}[(Q^0 + Q^1) * (GC^0 - GC^1)]$$

We have that Q^0 is total passenger travel (pkm) in the baseline scenario, Q^1 is total passenger travel (pkm) in the sub-use case (policy scenario), GC^0 is the generalised travel costs in the baseline scenario, and GC^1 is the generalised travel costs in the sub-use case. The generalised costs are "internal costs", like travel time (and travel quality), tickets or other travel/operating costs, and internal congestion and injury (risk) impacts.

The CBA module calculates consumer surplus changes mainly for three transport consumer groups: public transport passengers, $\Delta CS_{\text{public}}$, car occupants, ΔCS_{car}, and active travellers (cyclists/pedestrians), $\Delta CS_{\text{active}}$. The consumer surplus change is estimated in the same way for these three transport consumer groups. A common element in their generalised travel costs is travel time and its' valuation; internal injury impacts are also a common element, as well as internal congestion impacts for car and public transport passengers. For car occupants we add vehicle operating and ownership costs, and for public transport users we add the cost of fare. Separate calculations are carried out for the occupants of automated versus manual cars ($\Delta CS_{\text{autcar}}$ vs. $\Delta CS_{\text{mancar}}$). Under AUSS sub-use cases, there are additional calculations for either automated point-to-point shuttle passengers or automated on-demand shuttle-taxi passengers; and for automated ride-sharing cars (taxis) there will also be an additional calculation of consumer surplus change.

The CBA module carries out the calculations in vkm (replacing Q with T), which implies that valuation of time savings, individual tickets, etc. ("monetised impacts per pkm") are aggregated by the vehicle occupancy to the vkm. Estimation of consumer surplus change using vkm will in principal yield the same result as using pkm. Thus, for each transport mode we estimate the overall consumer surplus change, for all the travel activity in vkm, e.g.:

$$\Delta CS_{\text{public}} = {}^1\!/_2 \left[\left(T^0_{\text{public}} + T^1_{\text{public}}\right) * \left(GC^0_{\text{public}} - GC^1_{\text{public}}\right)\right]$$

The results might also be presented as the estimated consumer surplus change per year or per vkm (in the "new" policy case), e.g.: $\Delta CS_{\text{public}}/T^1_{\text{public}}$.

Adaptation of the rule-of-the-half to new transport modes – AUSS and automated shared taxis

The rule-of-a-half works well for aggregated transport mode groups, when the same transport modes are present in the baseline scenario and in the policy scenario. The simulated pkm and vkm of e.g. public transport under the policy scenario will comprise individual travellers who might have travelled similarly or not under the reference scenario; we don't know, but we only need to assess the aggregated consumer surplus change per transport mode (which also yields an estimated average change in consumer surplus per vkm for the mode).

However, for automated shuttles (point-to-point and on-demand), we only have travel activity under the policy scenario; there is no AUSS travel in reference. Likewise, we derive generalised costs of travel by AUSS under the policy scenario, but we do not know how the users of automated shuttles would travel without the deployment of automated shuttles (in the baseline scenario). The same applies to the automated ride sharing, a new type of taxi service under the passenger car use cases. There is no travel activity for shared taxis and automated shuttles in the reference, no $T^0_{\text{autcartaxi}}$ and no $T^0_{\text{autshuttle}}$; and subsequently no $GC^0_{\text{autcartaxi}}$ or $GC^0_{\text{autshuttle}}$. Two ways of handling this challenge can be proposed: i) either we always set $\Delta CS_{\text{autshuttle}}$ and $\Delta CS_{\text{autcartaxi}}$ to zero; or ii) we assume a "synthetic" transport mode distribution in the baseline, such that we can estimate a synthetic generalised cost of travel (e.g., $\widetilde{GC}^0_{\text{synthetic\_autshuttle}}$) in the baseline. We opt for this latter approach.

Table 3.1: New automated modes and the modal distribution they are assumed to replace

New automated mode	General description	Synthetic baseline mode distribution (shares in parenthesis)			
Point-to-point shuttle bus service connecting two modes	Automated bus service	Taxi (0%)	**Public transport** (80%)	Private car (10%)	Active transport (10%)
Point-to-point shuttle bus service in a large-scale network	Automated bus service	Taxi (0%)	**Public transport** (80%)	Private car (10%)	Active transport (10%)
On-demand shuttle bus service	Shared automated (maxi)taxi service	**Taxi** (70%)	Public transport (10%)	Private car (20%)	Active transport (0%)
Automated ride sharing (passenger car)	Automated version of existing shared taxi service	**Taxi** (70%)	Public transport (10%)	Private car (20%)	Active transport (0%)

We specify synthetic transport mode distributions for the baseline scenario for the (pkm and vkm of) transport consumers who use AUSS or automated shared riding (taxi). Table 3.1 summarizes the assumed synthetic baseline modal distributions. We stress that these are somewhat *ad hoc*, based on qualitative reasoning only. The transport mode written in boldface represents what we consider the closest (manual) substitute to the new automated mode. The mode shares in the synthetic baseline, for each new automated mode, are given in parentheses.

Thus, we specify one common synthetic mode distribution in baseline for "automated taxis" (where we assume user payments similar to existing use of manual taxis) and one common for automated point-to-point shuttles (where we assume user payments that will be part of existing ticket systems in public transport).

As indicated, we do not know $\tilde{T}^{0}_{\text{synthetic}}$, the travel lengths for the synthetic mode distribution in the baseline. We assume the amount of travel is the same in the baseline scenario as in the policy scenario, for those using the new automated mode. Thus, the change in consumer surplus for new modes is given, e.g., for point-to-point AUSS, by:

$$\Delta CS_{\text{autshuttle10}} = \left(\widetilde{GC}^{0}_{\text{synthetic\_autshuttle10}} - GC^{1}_{\text{authuttle10}}\right) * T^{1}_{\text{autshuttle10}}$$

Furthermore, it is given from theory that transport consumers will not switch to a mode such that their consumer surplus diminishes, *ceteris paribus*. Therefore, we add a restriction, e.g., for point-to-point AUSS:

$$\Delta CS_{\text{autshuttle10}} \geq 0 \quad Þ \quad \widetilde{GC}^{0}_{\text{synthetic\_autshuttle10}} \geq GC^{1}_{\text{authuttle10}}$$

The elements of the generalised costs

VTTS and internal congestion costs, transport consumers

The valuation of travel time savings (VTTS) is a main element in the transport consumers' generalised costs of travel (GC). As explained under section 2.2.1, the VTTS differs between transport modes,[75] as well as between travel purposes, and between travel under free flow versus congestion; and VTTS is fixed for a given year, but growing in real terms over time.[76] Thus, the VTTS under free flow, $w_{\text{hour\_mode\_flow}}$, is a weighted sum of VTTS for different travel purposes.[77] We can transfer the VTTS/hour for a given mode to VTTS/pkm, applying the travel time, in minutes per km ($h_{\text{min\_km\_flow\_mode}}$); which yields:

$$w_{\text{pkm\_mode\_flow}} = \frac{w_{\text{hour\_mode\_flow}}}{60} * h_{\text{min\_km\_flow\_mode}}$$

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[75] We lack VTTS for travel by taxi. For automated on-demand shuttles, we apply the same VTTS as for automated point-to-point shuttles, which is set to 0.85 of manual buses ($\omega_{\text{automation\_bus}}$). For ride sharing in passenger cars, we apply VTTS for passenger cars. There are however possible arguments for a different VTTS for travel by taxi. 1) travel by taxi could be considered more comfortable, thus bringing the VTTS downwards; 2) travel by taxi, also ride-sharing and on-demand shuttles, can be expected to be more common in affluent segments, thus possibly bringing the VTTS upwards. It is not obvious which of these effects is stronger; possibly there are other potential effects as well.

[76] The VTTS is the only valuation, or price, that is not a fixed real price in the CBA module, following Sartori et al. (2014), beyond possible underlying real price changes in PST variables, like the freight transport cost or the voc. Thus, we have that, e.g.: $w^{2021}_{\text{hour\_mode\_flow}} = w^{2020}_{\text{hour\_mode\_flow}} + \left(w^{2020}_{\text{hour\_mode\_flow}} * (\Delta\text{GDP} - \text{infl}) * 0.5\right)$. In PST, the default nominal GDP growth per capita (ΔGDP) is 1.5%; subtracting a default inflation (infl) of 1%, yields a real growth rate of 0.5%. Sartori et al. indicate an elasticity value of 0.5 for the (non-work time) VTTS, with respect to GDP per capita, implying a VTTS growth factor of 0.25% *per annum*.

[77] $w_{\text{hour\_mode\_flow}} = w_{\text{hour\_mode\_commute\_flow}} * s_{\text{commute\_mode}} + w_{\text{hour\_mode\_other\_flow}} * s_{\text{other\_mode}} + w_{\text{hour\_mode\_business\_flow}} * s_{\text{business\_mode}}$.

We can then obtain VTTS/vkm multiplying by occupancy:

$$w_{\text{vkm\_mode\_flow}} = w_{\text{pkm\_mode\_flow}} * n_{\text{occ\_mode}}$$

The CBA module is primarily calculating with respect to vkm.

VTTS under congestion, $w_{\text{hour\_mode\_cong}}$; is likewise a weighted sum of VTTS for different travel purposes; and $\left(w_{\text{hour\_mode\_cong}} - w_{\text{hour\_mode\_flow}}\right) > 0$ can be considered as representing the internal congestion cost per hour. Actually, we apply a fixed multiplier equal to: $w_{\text{hour\_mode\_cong}}/w_{\text{hour\_mode\_flow}} = \omega_{\text{cong}} = 1.42$, based on Wardman et al. (2016). The internal congestion cost per vkm, for passenger transport modes, is given as:

$$c_{\text{int\_cong\_vkm\_mode}} = w_{\text{vkm\_mode\_cong}} - w_{\text{vkm\_mode\_flow}}$$

That is, the internal congestion cost per vkm for passenger transport is equal to the additional VTTS per km in congestion relative to the valuation of travel time savings under free-flow conditions.

The share of travel time in congestion ($k_{\text{traveltime\_cong}}$) is higher than than the share of pkm in congestion ($k_{\text{pkm\_cong}} = 0.25$), for all modes experiencing congestion. It is calculated as:

$$k_{\text{traveltime\_cong\_mode}} = \frac{k_{\text{vkm\_cong}} * h_{\text{min\_km\_cong\_mode}}}{((1-k_{\text{vkm\_cong}}) * h_{\text{min\_km\_flow\_mode}}) + (k_{\text{vkm\_cong}} * h_{\text{min\_km\_cong\_mode}})}$$

The relative shares of travel time in congestion and free flow, respectively valued by $w_{\text{vkm\_mode\_cong}}$ and $w_{\text{vkm\_mode\_flow}}$, yields the traffic-condition weighted VTTS/vkm:

$$\overline{w}_{\text{vkm\_mode}} = \left(k_{\text{traveltime\_cong\_mode}} * w_{\text{vkm\_mode\_cong}}\right) + \left(\left(1 - k_{\text{traveltime\_cong\_mode}}\right) * w_{\text{vkm\_mode\_flow}}\right)$$

This is the main VTTS parameter applied in the CBA module,[78] which also includes the internal congestion costs for the transport mode.[79]

The GC in the CBA module is measured with vkm as unit. Thus, what enters GC_{mode} for the transport consumer, in the baseline scenario (0) and in the policy scenario (1), and subsequently ΔCS, is $\overline{w}_{\text{vkm\_mode}}$.[80] It is applied in the ΔCS together with the annual vkm (T_{mode}).

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[78] The (annual) sum over vkm of the weighted VTTS per vkm is: $\overline{W}_{\text{mode}} = \overline{w}_{\text{vkm\_mode}} * T_{\text{mode}}$. However, in the consumer surplus change, based on the rule-of-the-half, we apply VTTS/vkm ($\overline{w}_{\text{vkm\_mode}}$) in combination with the annual vkm (T_{mode}).

[79] Alternatively, if we want to separate the VTTS from the internal congestion cost, considering free flow VTTS as the "purer VTTS"; we use: $w^{\text{all\_flow}}_{\text{vkm\_mode}} = \left(\left(k_{\text{traveltime\_cong\_mode}}\right) + \left(1 - k_{\text{traveltime\_cong\_mode}}\right)\right) * w_{\text{vkm\_mode\_flow}}$. Thus, the sum of VTTS for the mode would be: $W^{\text{all\_flow}}_{\text{mode}} = w^{\text{all\_flow}}_{\text{vkm\_mode}} * T_{\text{mode}}$; and the sum of the congestion cost would be: $C_{\text{int\_cong\_mode}} = \left(k_{\text{traveltime\_cong\_mode}}\right) * \left(w_{\text{vkm\_mode\_cong}} - w_{\text{vkm\_mode\_flow}}\right) * T_{\text{mode}}$.

[80] Or, alternatively, if we separated VTTS from the internal congestion cost: $w^{\text{all\_flow}}_{\text{vkm\_mode}}$ plus $C_{\text{int\_cong\_vkm\_mode}}$.

Vehicle operating and ownership costs and fares, transport consumers
A weighted average of the vehicle operating and ownership costs (voc) for manual and automated passenger cars are provided by the PST. It is assumed that these are 67% for automated cars compared to manual cars:

$$c_{\text{voc\_vkm\_autcar}} = 0.67 * c_{\text{voc\_vkm\_mancar}}$$

The MPR scenario in the PST will fix the shares of automated (s_{autcar}) and manual (s_{mancar}) cars. In general, we derive the voc for manual cars as:

$$c_{\text{voc\_vkm\_mancar}} = \frac{c_{\text{voc\_vkm\_car}}}{s_{\text{mancar}} + 0.67 * s_{\text{autcar}}}$$

For active travellers ($c_{\text{voc\_vkm\_active}}$), the voc is derived by a fixed multiplier with respect to the voc of manual cars; if the share of cyclist and pedestrian pkm (or vkm) is equal, the multiplier ($\omega_{\text{voc\_active}}$) is about 0.1.

Those travelling by public transport, including automated point-to-point shuttles, will pay tickets, and those travelling by automated on-demand shuttles or automated ride-sharing cars will pay taxi fares. We assume payments per (single-person) trip for public transport ($\bar{p}_{\text{public\_trip}}$), assumed on average equal across all public transport types including point-to-point shuttles (and the the voc falls upon the public transport service providers).[81] We then derive average payment per vkm by dividing trip price by average trip length ($\bar{T}_{\text{trip}}$), set to the half the PST *commuting distance* (round trip) variable, for all travel purposes. Thus:

$$p_{\text{vkm\_public}} = \bar{p}_{\text{public\_trip}} / \bar{T}_{\text{trip}}$$

The taxi price is assumed to be a fare per pkm ($\bar{p}_{\text{taxi\_pkm}}$), equal for all on-demand shuttles and ride-sharing cars (and the voc falls upon the taxi service providers). For the single taxi service consumer, the fare is paid by km, but for occupancy above 1 the payment per vkm is higher than payment per vkm:

$$p_{\text{vkm\_taxi}} = \bar{p}_{\text{taxi\_pkm}} * n_{\text{occ}}$$

Thus, the voc (for private car occupants and active travellers) or fare (for public transport and taxi users) for the "consumption" of the transport mode, per vkm, enters GC_{mode} for the transport consumer, in the baseline scenario (0) and in the policy scenario (1), together with the annual vkm (T_{mode}). Actually, for automated shuttles and automated ride-sharing cars, we will only have observations in the policy scenario (1). Under these sub-use cases we derive "synthetic" generalised costs for the baseline and apply the same distance as estimated for the policy scenario (Table 3.1).

Internal crash costs, transport consumers
Crashes, resulting in material damages and/or injuries/fatalities, have both an external part (costs inflicted upon other infrastructure users and the rest of society) and an internal part (costs that the infrastructure user inflicts upon himself/herself). The deriving

[81] We apply fixed multipliers for deriving the voc of other passenger vehicles; with respect to automated cars for automated shuttles, and with respect to manual cars for buses. The voc for LCVs are based on Hu et al. (2021a), where the underlying annual cost elements are set three times higher for HGV than for LCV.

of total crash costs and the external part is explained below. The internal crash cost for a transport mode per vkm, which enters the GC_{mode} for the transport consumer, can be stated as:

$$c_{\text{int\_crash\_vkm\_mode}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_mode}}\right) * c_{\text{crash\_vkm\_mode}}$$

For AUSS and ride-sharing taxi users we assume that the internal crash costs, that also include material damage, are shared equally between the passengers and the transport service provider. Regarding other (manual) public transport, its crash risk is not included in the PST variable; so, the crash costs for (manual) public transport is fixed to zero. For AUSS and ride-sharing taxi users, $c_{\text{int\_crash\_vkm\_mode}}/2$ enters the GC_{mode} (while the other half enters the costs for the transport service providers).

Summarising generalised cost elements, transport consumers
Thus, what enters the GC_{mode} for the transport consumer comprise $\bar{w}_{\text{vkm\_mode}}$,[82] then $c_{\text{voc\_vkm\_mode}}$ or $p_{\text{vkm\_public}}$ or $p_{\text{vkm\_taxi}}$, and finally $c_{\text{int\_crash\_vkm\_mode}}$ (for car occupants and active travellers) or $c_{\text{int\_crash\_vkm\_mode}}/2$ for automated shuttle users and automated ride-sharing users (as we divide the internal crash costs between passengers and service providers).

3.2.2 Details on consumer surplus changes for transport mode users

Passenger car users

Travel time change and valuation of travel time savings, including internal congestion
Travel time changes affect the generalised cost functions of transport consumers. As described above, these changes are monetised by the value of travel time savings (VTTS), that vary with respect to travel purpose, traffic conditions, automation, etc. As default VTTS/hour we apply the purpose-weighted estimates (from Table 2.10). The VTTS/hour estimates for manual and automated passenger cars, in free flow vs. congestion, are displayed in the following table.

Table 3.2: Valuation of travel time savings for manual and autonomous passenger cars by traffic condition, weighted by travel purpose, EU-28 - GDP/capita in EUR2020 (*30,500*)

	Manual car occupant		**Autonomous car occupant**	
	Free flow	**Congestion**	**Free flow**	**Congestion**
VTTS (€/hour)	*8.99*	*12.77*	*5.84*	*8.30*
Multiplicator		*1.42*	*0.65*	*1.42*

Source: Table 2.10, with only rounding error differences.

We transfer the VTTS/hour to VTTS/pkm, applying the travel time (which is governed by the PST variable *travel time*, $h_{\text{min\_5km\_car}}$, the congestion travel time also by *congestion*, $d_{\text{sec\_km}}$); the travel time applied is measured in minutes per km ($h_{\text{min\_km\_car}}$). In the CBA module, the calculations are performed separately for automated cars and manual cars.

[82] Or alternatively, if separating internal congestion costs from VTTS: $w_{\text{vkm\_mode}}^{\text{all\_flow}}$ plus $c_{\text{int\_cong\_vkm\_mode}}$.

So, firstly the VTTS/pkm is derived for automated and manual in free flow and in congestion.

The VTTS/pkm in free flow for automated cars is:

$$w_{\text{pkm\_autcar\_flow}} = \frac{w_{\text{hour\_autcar\_flow}}}{60} * h_{\text{min\_km\_flow\_autcar}}$$

The VTTS/pkm in congestion for AVs is:

$$w_{\text{pkm\_autcar\_cong}} = \frac{w_{\text{hour\_autcar\_cong}}}{60} * h_{\text{min\_km\_cong\_autcar}}$$

The VTTS/pkm in free flow for automated cars is:

$$w_{\text{pkm\_mancar\_flow}} = \frac{w_{\text{hour\_mancar\_flow}}}{60} * h_{\text{min\_km\_flow\_mancar}}$$

The VTTS/pkm in congestion for manual cars is:

$$w_{\text{pkm\_mancar\_cong}} = \frac{w_{\text{hour\_mancar\_cong}}}{60} * h_{\text{min\_km\_cong\_mancar}}$$

While automated and manual cars are assumed to have the same travel time in free flow, the automated cars are assumed to suffer relatively less delay under congestion than manual cars:

$$h_{\text{min\_km\_cong\_autcar}} = h_{\text{min\_km\_cong\_mancar}} - \left(h_{\text{min\_km\_cong\_mancar}} * 0.17\right)$$

That is, the automated cars have 17% lower travel time than manual cars under congestion. This influences on the derived VTTS per distance driven.

Then the traffic-condition-weighted average VTTS/vkm is derived, for automated and manual passenger cars. As detailed under 3.2.1, the relative shares of pkm and vkm valued by VTTS in congestion, $w_{\text{hour\_car\_cong}}$, and VTTS in free flow, $w_{\text{hour\_car\_flow}}$, can be derived by use of the share of the travel time in congestion, $k_{\text{traveltime\_cong\_car}}$, which is larger than the share of pkm and vkm in congestion, $k_{\text{vkm\_cong\_car}} = 0.25$.[83] We multiply VTTS/pkm by occupancy, $n_{\text{occ\_car}}$, as VTTS/vkm must also be passenger-weighted:

$$\overline{w}_{\text{vkm\_autcar}} = n_{\text{occ\_autcar}} * \left(\left(k_{\text{traveltime\_cong\_autcar}} * w_{\text{pkm\_autcar\_cong}}\right) + \left(\left(1 - k_{\text{traveltime\_cong\_autcar}}\right) * w_{\text{pkm\_autcar\_flow}}\right)\right)$$

and

$$\overline{w}_{\text{vkm\_mancar}} = n_{\text{occ\_mancar}} * \left(\left(k_{\text{traveltime\_cong\_mancar}} * w_{\text{pkm\_mancar\_cong}}\right) + \left(\left(1 - k_{\text{traveltime\_cong\_mancar}}\right) * w_{\text{pkm\_mancar\_flow}}\right)\right)$$ [84]

[83] A fixed default of 25% of pkm is assumed to be carried out under congestion ($k_{\text{pkm\_cong}} = 0.25$). As the speed under congestion is lower, the travel time per km longer, the share of travel time in congestion ($k_{\text{traveltime\_cong}}$) is higher than the share of pkm in congestion. This is of importance for the internal congestion cost, as this is based on the addendum to the VTTS under congestion (Table 2.10). For the internal congestion cost we derive the share of travel time spent under congestion (versus free flow) applying the average delay in seconds per vkm (from the PST), as well as travel time assumptions for each mode under free-flow, $k_{\text{traveltime\_cong\_mode}} = \frac{k_{\text{pkm\_cong\_mode}} * h_{\text{min\_km\_cong\_mode}}}{\left(k_{\text{pkm\_flow\_mode}} * h_{\text{min\_km\_flow\_mode}}\right) + \left(k_{\text{pkm\_cong\_mode}} * h_{\text{min\_km\_cong\_mode}}\right)}$; as specified under section 2.2.2.

[84] A weighted VTTS per vkm for passenger cars is a weighted average that also depends on the MPR (s_{autcar}) of automated cars (1st gen. plus 2nd gen.): $\overline{w}_{\text{vkm\_car}} = \left(s_{\text{autcar}} * \overline{w}_{\text{vkm\_autcar}}\right) + \left(\left(1 - s_{\text{autcar}}\right) * \overline{w}_{\text{vkm\_mancar}}\right)$.

As clarified in section 3.2.1, these weighted VTTS/vkm also include the internal congestion costs for the passenger car occupants.[85] Annual estimates of VTTS can also be derived, but the formula for estimating consumer surplus changes is based on using the VTTS/vkm with the annual vkm.[86]

<u>Vehicle operating and ownership costs (voc)</u>
The voc is included in the internal costs, the generalised costs for people travelling by passenger cars. As described in 2.2.1 and 3.2.1, the calculation of voc for passenger cars relies directly on the PST variable *vehicle operating cost*, "direct outlays for operating a vehicle per kilometre of travel". The PST provides a weighted voc for manual and automated cars ($c_{\text{voc\_vkm\_car}}$); the automated having a voc that is 67% of voc of manual. The weighted voc for cars will then depend on the market penetration rate of automated cars. The initial default voc (see

[85] If we consider free flow VTTS as the "purer VTTS" and want to separate VTTS from internal congestion costs; we apply instead: $w_{\text{vkm\_car}}^{\text{all\_flow}} = \left(\left(k_{\text{traveltime\_cong\_car}}\right) + \left(1 - k_{\text{traveltime\_cong\_car}}\right)\right) * w_{\text{vkm\_car\_flow}}$. The internal congestion cost per vkm, $c_{\text{int\_cong\_vkm\_car}} = w_{\text{vkm\_car\_cong}} - w_{\text{vkm\_car\_flow}}$, is then applied for $k_{\text{traveltime\_cong\_car}}$. The (annual) sum of VTTS (not including congestion) would be: $W_{\text{car}}^{\text{all\_flow}} = w_{\text{vkm\_car}}^{\text{all\_flow}} * T_{\text{car}}$; and the (annual) sum of the internal congestion cost: $C_{\text{int\_cong\_car}} = \left(k_{\text{traveltime\_cong\_car}}\right) * \left(w_{\text{vkm\_car\_cong}} - w_{\text{vkm\_car\_flow}}\right) * T_{\text{car}}$.

[86] Total (annual) travel time and internal congestion costs for passenger car occupants can simply be found by multiplying the VTTS/vkm by the total travel length by passenger car vehicles (T_{autcar} and T_{mancar}, derived by use of the PST variables *amount of travel* in pkm, Q, and *modal split*, combined with assumed occupancies in cars and public transport, under passenger transport scenarios). Hence $\overline{W}_{\text{autcar}} = \overline{w}_{\text{vkm\_autcar}} * T_{\text{autcar}}$ and $\overline{W}_{\text{mancar}} = \overline{w}_{\text{vkm\_mancar}} * T_{\text{mancar}}$.

Table 2.13) is €0.36 for automated cars and €0.54 for manual cars, at the EU-28 cost level of GDP/capita average of 30,500 EUR2020. The voc can be altered over time and across scenarios, governed by the PST.

The voc per vkm for manual cars is given by:

$$c_{\text{voc\_vkm\_mancar}} = \frac{c_{\text{voc\_vkm\_car}}}{(1-s_{\text{autcar}})+0.67*s_{\text{autcar}}}$$

And hence, the voc per vkm for autonomous cars is:

$$c_{\text{voc\_vkm\_autcar}} = 0.67 * c_{\text{voc\_vkm\_mancar}}$$

These are the voc estimates that enter the generalised costs (GC) for car occupants, respectively, under the baseline scenario (0) and the policy scenario (1).[87]

<u>Internal costs of crashes (fatality, injury, material damage)</u>
As described in section 3.2.1, total crash costs from the transport activity is derived from the PST variable *road safety total effect*, which contains the crash risk per vkm ($n^{\text{crash/vkm}}$), multiplied by a weighted average crash cost estimate ($\bar{C}_{\text{crash}} = €14{,}800$, for EU-28-GDP/capita equal to EUR2020*30,500*). This average crash value per vkm, for all included modes ($\bar{c}_{\text{crash\_vkm}}$) is multiplied by vkm of included transport modes (T_{safety}) to estimate total annual crash costs (C_{crash}). We distribute the total annual crash cost across the included transport modes, applying relative crash cost ($\bar{\theta}_{\text{crash\_mode}}$, see Table 2.22); the total annual crash cost will comprise both internal and external crash costs.

The included transport modes differ slightly between passenger transport scenarios ($T_{\text{safety\_passenger}}$) and freight scenarios ($T_{\text{safety\_freight}}$); public transport is always excluded.[88] But, passenger cars are always included among the transport modes for modal crash cost estimation.

The formulas for deriving the crash cost (per vkm) per mode ($c_{\text{crash\_vkm\_mode}}$), internal and external, are shown in sections 2.2.3 and 3.2.1. Firstly, the (annual) crash costs allocated to automated cars are:

$$C_{\text{crash\_autcar}} = \tilde{C}_{\text{crash\_autcar}} * \left(\frac{n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}}{\tilde{C}_{\text{crash\_autcar}} + \cdots + \tilde{C}_{\text{crash\_modes5}}}\right)$$

and, similarly, for manual cars:

$$C_{\text{crash\_mancar}} = \tilde{C}_{\text{crash\_mancar}} * \left(\frac{n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}}{\tilde{C}_{\text{crash\_mancar}} + \cdots + \tilde{C}_{\text{crash\_modes5}}}\right)$$

The term $\tilde{C}_{\text{crash\_mode}} = \left(\left(n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}\right) * \left(\frac{T_{\text{mode}}}{T_{\text{safety}}}\right) * \bar{\theta}_{\text{crash\_mode}}\right)$ is the unscaled allocated share of crash cost to the specific mode based on its relative crash cost rate ($\bar{\theta}_{\text{crash\_mode}}$); the unscaled costs of other modes within are summed in the denominators of the expressions for $C_{\text{crash\_autcar}}$ and $C_{\text{crash\_mancar}}$.

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[87] The annual voc is: $C_{\text{voc\_autcar}} = c_{\text{voc\_vkm\_autcar}} * T_{\text{autcar}}$ and $C_{\text{voc\_mancar}} = c_{\text{voc\_vkm\_mancar}} * T_{\text{mancar}}$.

[88] As clarified in sections 2.2.3 and 3.2.1, $T_{\text{safety\_passenger}} = (T_{\text{autcar}} + T_{\text{mancar}} + T_{\text{active}} + T_{\text{autshuttle}})$; and $T_{\text{safety\_freight}} = (T_{\text{autfreight}} + T_{\text{manfreight}} + T_{\text{autcar}} + T_{\text{mancar}} + T_{\text{active}})$.

The attributed crash cost per vkm for automated cars is then just:

$$c_{\text{crash\_vkm\_autcar}} = \frac{C_{\text{crash\_autcar}}}{T_{\text{autcar}}}$$

and

$$c_{\text{crash\_vkm\_mancar}} = \frac{C_{\text{crash\_mancar}}}{T_{\text{mancar}}}$$

The crash costs allocated to transport modes have different shares of external and internal parts (see Table 2.22). For passenger cars, the external share ($\bar{\alpha}_{\text{ext\_crash\_car}}$) is set to 50%; thus the internal ($1 - \bar{\alpha}_{\text{ext\_crash\_car}}$) is also 50%; with no differentiation between manual and automated. Thus, the internal crash cost per vkm for automated car users is then:

$$c_{\text{crash\_int\_vkm\_autcar}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_car}}\right) * \frac{C_{\text{crash\_autcar}}}{T_{\text{autcar}}}$$

and

$$c_{\text{crash\_int\_vkm\_mancar}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_car}}\right) * \frac{C_{\text{crash\_mancar}}}{T_{\text{mancar}}}$$

These are the cost elements for private car users that enters the estimated generalised costs (GC), respectively under the baseline scenario (0) and the policy scenario (1).[89]

The consumer surplus change for passenger car users

The general format of the consumer surplus change, from baseline (reference) to policy scenario, is: $\Delta CS_{\text{mode}} = {}^{1}\!/_{2}\,[(T^{0}_{\text{mode}} + T^{1}_{\text{mode}}) * (GC^{0}_{\text{mode}} - GC^{1}_{\text{mode}})]$. Summarising the three (or four) internal cost components for manual cars and automated cars, we can estimate the following change:

$$\Delta CS_{\text{car}} = {}^{1}\!/_{2}\left[(T^{0}_{\text{car}} + T^{1}_{\text{car}}) * \left(\left(\bar{w}^{0}_{\text{vkm\_car}} + c^{0}_{\text{voc\_vkm\_car}} + \left(\bar{\alpha}_{\text{int\_crash\_car}} * c^{0}_{\text{crash\_vkm\_car}}\right)\right) - \left(\bar{w}^{1}_{\text{vkm\_car}} + c^{1}_{\text{voc\_vkm\_car}} + \left(\bar{\alpha}_{\text{int\_crash\_car}} * c^{1}_{\text{crash\_vkm\_car}}\right)\right)\right)\right]$$

Thus, $GC^{0}_{\text{car}} = \left(\bar{w}^{0}_{\text{vkm\_car}} + c^{0}_{\text{voc\_vkm\_car}} + \left(\bar{\alpha}_{\text{int\_crash\_car}} * c^{0}_{\text{crash\_vkm\_car}}\right)\right)$, and vice versa for GC^{1}_{car} (and $\bar{\alpha}_{\text{int\_crash\_car}} = 1 - \bar{\alpha}_{\text{ext\_crash\_car}}$). As pointed out, we estimate separate consumer surplus changes for automated cars ($\Delta CS_{\text{autcar}}$) and manual cars ($\Delta CS_{\text{mancar}}$).

Public transport users (beyond AUSS)

Travel time change and valuation of travel time savings, including internal congestion

It is important to bear in mind that public transport (beyond point-to-point AUSS) normally comprises multiple modes; we have established a default that might be applicable to larger European cities.[90] However, the PST/CBA user should have the opportunity to adjust our default. Moreover, there is an underlying assumption in the PST

[89] The annual internal crash costs are $C_{\text{crash\_int\_autcar}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_car}}\right) * C_{\text{crash\_autcar}}$, for automated car users, and $C_{\text{crash\_int\_mancar}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_car}}\right) * C_{\text{crash\_mancar}}$, for manual car users.

[90] That is, 45% pkm rail-based (the sum of 15% light rail / tram, 15% metro/subway, and 15% of other heavy rail), with average weighted occupancy of 90, and 55% pkm road-based public transport (buses), with average weighted occupancy of 18; the overall weighted occupancy is 50 (see **Error! Reference source not found.**).

that only AUSS will be automated, the remaining public transport will remain manual; for that sake and other obvious reasons we treat the AUSS on its own, below.

As default VTTS we apply the travel-purpose-weighted estimates (from Table 2.10). The VTTS/hour estimates for public transport represent weighted averages of road-based (manual bus) VTTS/hour and rail-based VTTS/hour, in free flow vs. congestion, i.e.: $w_{\text{hour\_public\_flow}} = s_{\text{vkm\_public\_rail}} * w_{\text{hour\_rail}} + (1 - s_{\text{vkm\_public\_rail}}) * w_{\text{hour\_manbus\_flow}}$; and likewise: $w_{\text{hour\_public\_cong}} = s_{\text{vkm\_public\_rail}} * w_{\text{hour\_rail}} + (1 - s_{\text{vkm\_public\_rail}}) * w_{\text{hour\_manbus\_cong}}$. The vkm-weighted VTTS/hour estimates are displayed in the following table.

Table 3.3: Valuation of travel time savings for (manual) public transport (vkm-weighted average of road-based and rail-based) by traffic condition, weighted by travel purpose, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

	Bus user		**Rail user**		**Public transport user**	
	85%		*15%*		*100%*	
	Free flow	**Congestion**	**Free flow**	**Congestion**	**Free flow**	**Congestion**
VTTS (€/hour)	*5,30*	*7,53*	*7,82*	*7,82*	*5,68*	*7,58*
Multiplicator	*0,59*	*1,42*	*0,87*	*1,00*		

Source: Table 2.10, with only rounding error differences.

We transfer the VTTS/hour to VTTS/pkm, applying the travel time. The travel time for (manual) buses in free flow is set with respect to the travel time by car, using a fixed multiplier of 1.2: $h_{\text{min\_km\_flow\_manbus}} = h_{\text{min\_km\_flow\_car}} * 1.2$. The congestion travel time, follows the delay for cars: $h_{\text{min\_km\_cong\_manbus}} = h_{\text{min\_km\_flow\_manbus}} + (d_{\text{sec\_km\_mancar}}/60)$. For simplicity we set the average travel time by rail equal to the free-flow average by car ($h_{\text{min\_km\_rail}} = h_{\text{min\_km\_flow\_car}}$), implicitly assuming no congestion effects in rail-based public transport. The vkm-weighted travel times for (rail-based and road-based) public transport, in free flow and congestion, have been derived from these (see section 2.2.1 and Table 2.3): $h_{\text{min\_km\_flow\_public}} = s_{\text{vkm\_public\_rail}} * h_{\text{min\_km\_rail}} + (1 - s_{\text{vkm\_public\_rail}}) * h_{\text{min\_km\_flow\_manbus}}$; and $h_{\text{min\_km\_cong\_public}} = s_{\text{vkm\_public\_rail}} * h_{\text{min\_km\_rail}} + (1 - s_{\text{vkm\_public\_rail}}) * h_{\text{min\_km\_cong\_manbus}}$.

Then we can derive the VTTS/pkm, respectively in free flow and in congestion:

$$w_{\text{pkm\_public\_flow}} = \frac{w_{\text{hour\_public\_flow}}}{60} * h_{\text{min\_km\_flow\_public}}$$

and

$$w_{\text{pkm\_public\_cong}} = \frac{w_{\text{hour\_public\_cong}}}{60} * h_{\text{min\_km\_cong\_public}}$$

And then the traffic-condition-weighted average VTTS/vkm can be derived. As detailed under 3.2.1, the relative shares of pkm and vkm valued by VTTS in congestion, $w_{\text{hour\_public\_cong}}$, and VTTS in free flow, $w_{\text{hour\_public\_flow}}$, can be derived by use of the share of the travel time applied under congestion, $k_{\text{traveltime\_cong\_public}}$, which is larger than the share of pkm and vkm in congestion, $k_{\text{vkm\_cong\_public}} = 0.25$. We multiply VTTS/pkm by (vkm-weighted) occupancy in public transport, $n_{\text{occ\_public}} = 28$, as VTTS/vkm must also be passenger-weighted:

$$\overline{w}_{\text{vkm\_public}} = n_{\text{occ\_public}} * \left((k_{\text{traveltime\_cong\_public}} * w_{\text{pkm\_public\_cong}}) + ((1 - k_{\text{traveltime\_cong\_public}}) * w_{\text{pkm\_public\_flow}}) \right)$$

As clarified in section 3.2.1, these weighted VTTS/vkm also include the internal congestion costs for the public transport passengers. Hence, it is VTTS/vkm ($\overline{w}_{\text{vkm\_public}}$)

that enters the estimated generalised costs (GC) for public transport "consumers", respectively under baseline (0) and policy scenario (1).[91]

Ticket costs (individual single-trip tickets)
The ticket cost for public transport users is included in the internal costs, the generalised costs. The calculation of ticket costs relies on the PST variable *commuting distance*; divided by two it yields the average length of a commuting single trip ($\bar{T}_{\text{trip\_commute}}$), and as a simplification we apply this trip length for all purposes ($\bar{T}_{\text{trip}} = \bar{T}_{\text{trip\_commute}}$). The total (annual) number of passenger trips by public transport is then estimated as: $n_{\text{trip\_public}} = Q_{\text{public}}/\bar{T}_{\text{trip}}$.

We apply an average single-person single-trip ticket cost for European cities, i.e., 2.70 EUR2020 ($\bar{p}_{\text{public\_trip}}$), at the EU-28 cost level of GDP/capita average of 30,500 EUR2020. Total annual payment equals: $P_{\text{public}} = \bar{p}_{\text{public\_trip}} * n_{\text{trip\_public}}$. Then the payment per vkm for public transport equals $p_{\text{vkm\_public}} = P_{\text{public}}/T_{\text{public}}$.

So, the ticket costs per vkm for public transport passengers will be:

$$p_{\text{vkm\_public}} = \left(\bar{p}_{\text{public\_trip}} * \left(Q_{\text{public}}/\bar{T}_{\text{trip}}\right)\right) \Big/ \left(Q_{\text{public}}/n_{\text{occ\_public}}\right) = P_{\text{public}} \Big/ T_{\text{public}}$$

That is, the annual payment (trip cost times annual trips) divided by public transport annual vkm (public transport pkm divided by occupancy). The payment per vkm ($p_{\text{vkm\_public}}$) is what enters the estimated generalised costs (GC) for public transport passengers, respectively under the baseline scenario (0) and the policy scenario (1).[92]

Internal costs of crashes (fatality, injury, material damage)
Public transport (beyond AUSS) is not included among the transport modes within the PST variable *road safety total effect*; so deriving crash costs attributed to public transport is unattainable for the CBA module; these are fixed to zero in the baseline as well as in policy scenarios.

The consumer surplus change for public transport users
Summarising the two (or three) internal cost components for public transport users, we can estimate the following consumer surplus change:

$$\Delta CS_{\text{public}} = {}^{1}\!/_{2}\left[\left(T^{0}_{\text{public}} + T^{1}_{\text{public}}\right) * \left(\left(\bar{w}^{0}_{\text{vkm\_public}} + p^{0}_{\text{vkm\_public}} + 0\right) - \left(\bar{w}^{1}_{\text{vkm\_public}} + p^{1}_{\text{vkm\_public}} + 0\right)\right)\right]$$

Thus, $GC^{0}_{\text{public}} = \left(\bar{w}^{0}_{\text{vkm\_public}} + p^{0}_{\text{vkm\_public}} + 0\right)$, and vice versa for GC^{1}_{public} (and the 0 refers to zero crash costs).

AUSS users (point-to-point and on-demand) plus ride-sharing taxi users
Travel time change and valuation of travel time savings, including internal congestion

[91] The annual travel time and internal congestion costs for public transport passengers are found when multiplying the VTTS/vkm by the total travel length by public transport: $\bar{W}_{\text{public}} = \bar{w}_{\text{vkm\_public}} * T_{\text{public}}$.

[92] As clarified, the annual ticket payment by the public transport users is: $P_{\text{public}} = p_{\text{vkm\_public}} * T_{\text{public}}$.

The AUSS only exists under their particular sub-use case implementations. The point-to-point AUSS is handled as other public transport, while the on-demand AUSS is handled as a type of taxi. Automated ride-sharing passenger cars are also handled as a type of taxi. As default VTTS for automated shuttles, point-to-point as well as on-demand, we apply the travel-purpose-weighted estimates for automated shuttles/buses (from Table 2.10). The VTTS/hour estimates, in free flow vs. congestion, are displayed in the following table.[93]

Table 3.4: Valuation of travel time savings for shuttle buses by traffic situation, weighted by travel purpose, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

	Automated shuttle bus users	
	Free flow	**Congestion**
VTTS (€/hour)	*4,51*	*6,40*
Multiplicator	*0,85*	*1,42*

Source: Table 2.10, with only rounding error differences.

We transfer the VTTS/hour to VTTS/pkm, applying the travel time. As for manual buses, the travel time for automated shuttles in free flow is set with respect to the travel time by car, using a fixed multiplier of 1.2: $h_{\text{min\_km\_flow\_autshuttle}} = h_{\text{min\_km\_flow\_car}} * 1.2$. The congestion travel time for automated shuttles is set with respect to manual buses, following the relative relationship between automated and manual cars: $h_{\text{min\_km\_cong\_autshuttle}} = h_{\text{min\_km\_cong\_manbus}} - (h_{\text{min \_km\_cong\_manbus}} * 0.17)$. Thus, the travel time by automated shuttles is assumed to be relatively less affected by congestion than manual buses; having 17% lower travel time. The VTTS/pkm is then, in free flow:

$$w_{\text{pkm\_shuttle\_flow}} = \frac{w_{\text{hour\_shuttle\_flow}}}{60} * h_{\text{min\_km\_flow\_shuttle}}$$

and in congestion the VTTS/pkm is:

$$w_{\text{pkm\_shuttle\_cong}} = \frac{w_{\text{hour\_shuttle\_cong}}}{60} * h_{\text{min\_km\_cong\_shuttle}}$$

Then the traffic-condition-weighted average VTTS/vkm is derived; multiplying VTTS/pkm by occupancy in automated shuttle buses, $n_{\text{occ\_autshuttle}}$, to obtain the correctly passenger-weighted VTTS/vkm:

$$\bar{w}_{\text{vkm\_autshuttle}} = n_{\text{occ\_autshuttle}} * \left(\left(k_{\text{traveltime\_cong\_autshuttle}} * w_{\text{pkm\_autshuttle\_cong}} \right) + \left(\left(1 - k_{\text{traveltime\_cong\_autshuttle}} \right) * w_{\text{pkm\_autshuttle\_flow}} \right) \right)$$

The average occupancy will vary between different types of shuttles; it is 5 (50%*10) in point-to-point shuttles, and either 4 (50%*8) or 7.5 (50%*15) in on-demand shuttles. The occupancy will have an influence on VTTS/vkm.

As clarified in section 3.2.1, the weighted VTTS/vkm also include the internal congestion costs for the public transport passengers.

[93] For users of automated ride-sharing passenger cars, we assume the same VTTS/hour as for occupants of automated cars in general. The VTTS/pkm will also be equal between automated shared taxis and (private) automated cars in general. The VTTS/vkm might be slightly different though, if the occupancy in automated ride-sharing cars is different from (higher than) the occupancy in (private) automated cars.

Thus, it is the VTTS/vkm ($\bar{w}_{\text{vkm\_autshuttle}}$) that enters the estimated generalised costs (GC) for automated shuttle "consumers", under the policy scenario (1); there is neither AUSS nor automated ride-sharing in the baseline scenario (0).[94]

Ticket costs (individual single-trip tickets) and taxi fare costs
The ticket cost and taxi fare cost for automated shuttle users, respectively point-to-point and on-demand, is included in the internal costs, the generalised costs. The taxi fare costs for automated ride-sharing cars can be handled similarly as for the on-demand taxi shuttles.

Under the policy scenarios for automated shuttles and automated ride-sharing cars, we apply trip lengths from the underlying micro-simulations for the PST (see section 2.4.4). These underlying figures also comprise the pkm and vkm.

So for automated point-to-point shuttles, similarly to (other) public transport, total annual payment equals: $P_{\text{autshuttle10}} = \bar{p}_{\text{public\_trip}} * n_{\text{trip\_autshuttle10}}$, applying the same single-person single-trip ticket cost of 2.70 EUR$_{2020}$ ($\bar{p}_{\text{public\_trip}}$), at the EU-28 cost level of GDP/capita average of 30,500 EUR$_{2020}$. The payment per vkm for point-to-point shuttles equals:

$$p_{\text{autshuttle10\_vkm}} = P_{\text{autshuttle10}} / T_{\text{autshuttle10}}$$

Users of automated on-demand shuttles and automated ride-sharing cars are assumed to pay the same fare per pkm ($\bar{p}_{\text{taxi\_pkm\_autshuttle15}} = \bar{p}_{\text{taxi\_pkm\_autshuttle8}} = \bar{p}_{\text{taxi\_pkm\_autcar}} = \bar{p}_{\text{taxi\_pkm}}$); our default is €1.10 per pkm, at the EU-28 cost level of GDP/capita average of 30,500 EUR$_{2020}$. Their annual payment is then, e.g.: Then, annual taxi payment is calculated as, e.g., for on-demand shuttles with 8-seats capacity: $P_{\text{autshuttle8}} = \bar{p}_{\text{taxi\_pkm}} * Q_{\text{autshuttle8}}$. The payment per vkm for the on-demand shuttle buses will then equal:

$$p_{\text{vkm\_autshuttle8}} = P_{\text{autshuttle8}} / T_{\text{autshuttle8}}$$

The expressions are equivalent for on-demand shuttles with 15-seats capacity and for automated ride-sharing cars.

What enters the estimated generalised costs (GC), under the policy scenario (1), will then be $p_{\text{vkm\_autshuttle10}}$ for automated point-to-point shuttle passengers. For automated taxi users, it will be $p_{\text{vkm\_autshuttle8}}$ or $p_{\text{vkm\_autshuttle15}}$ or $p_{\text{vkm\_autcartaxi}}$.[95]

Internal costs of crashes (fatality, injury, material damage)
It is explained under passenger cars (above), as well as in sections 2.2.3 and 3.2.1, how total crash costs from the transport activity is derived first. Then the total crash costs are attributed to the included transport modes based on their relative crash cost rate ($\bar{\theta}_{\text{crash\_autshuttle}}$ and $\bar{\theta}_{\text{crash\_autcar}}$, see Table 2.22.). The automated shuttles are included in

[94] The annual VTTS is, e.g.: $\bar{W}_{\text{autshuttle}} = \bar{w}_{\text{vkm\_autshuttle}} * T_{\text{autshuttle}}$.

[95] Annual ticket costs are: $P_{\text{autshuttle10}} = p_{\text{vkm\_autshuttle10}} * T_{\text{autshuttle10}}$. For automated on-demand shuttles, the annual taxi payment is, e.g.: $P_{\text{autshuttle8}} = p_{\text{vkm\_autshuttle8}} * n_{\text{occ\_autshuttle8}} * T_{\text{autshuttle8}}$; and equivalently for automated ride-sharing cars.

PST variable *road safety total effect*, the crash risk per vkm ($n^{\text{crash/vkm}}$), under AUSS passenger transport scenarios. Then the vkm by automated shuttles is included in the transport mode vkm that is relevant, together with the vkm by automated and manual passenger cars and active transport ($T_{\text{safety\_passenger}}$). Likewise, the vkm of automated ride-sharing cars is included under this passenger-car SUC.

The formulas for deriving the crash cost (per vkm) per mode ($c_{\text{crash\_mode}}$), internal plus external, are shown in sections 2.2.3 and 3.2.1. The deriving of (annual) crash costs allocated to automated cars ($C_{\text{crash\_autcar}}$) has also been shown under the sub-section about passenger cars (above). The (annual) crash costs allocated to automated shuttles ($C_{\text{crash\_autshuttle}}$) are derived in the same way.

Regarding the share of external versus internal crash costs, the automated shuttle buses are assumed to have an external share of 60% and automated cars 50% (see Table 2.22). Thus, for automated shuttles, the internal share is ($1 - \bar{\alpha}_{\text{ext\_crash\_autshuttle}}$) is 40%, while it is 50% for automated cars. However, the passengers of point-to-point shuttles and taxis are not expected to carry all the internal crash costs attributed to the vehicle. Most of the crashes will only imply material damage to the vehicle, and although the relative value weight of injury and fatality crashes is much higher, assuming material costs to represent about 50% of total crash costs seems appropriate (see Table 2.21).

Thus, what enters the estimated generalised costs for automated shuttle and ride-sharing taxi passengers, will have a slightly different formulation. The internal crash cost per vkm for automated shuttle-bus users will be:

$$c_{\text{crash\_int\_vkm\_autshuttle\_pass}} = c_{\text{crash\_int\_vkm\_autshuttle}} / 2 = \left(\left(1 - \bar{\alpha}_{\text{ext\_crash\_autshuttle}} \right) * c_{\text{crash\_vkm\_autshuttle}} \right) / 2$$

The crash cost per vkm, and subsequently the internal (share of) crash costs per vkm, might differ between the automated shuttle types; the higher the occupancy, the lower is the cost per vkm per passenger, *ceteris paribus*.

The internal crash cost share for passengers ($c_{\text{crash\_int\_vkm\_autshuttle\_pass}}$) is what enters the estimated generalised costs (GC) under the policy scenario (1). The expression for automated ride-sharing car passengers is equivalent, building on the crash costs attributed to automated cars. The other half of the internal crash costs for automated shuttle buses and ride-sharing taxis is assumed by the AUSS and taxi service providers.

<u>The consumer surplus change for AUSS and automated ride-sharing taxi users</u>
Summarising the three (or four) internal cost components for automated point-to-point shuttle buses, we can estimate the following consumer surplus change:

$$\Delta CS_{\text{autshuttle10}} = {}^{1}/_{2} \left[\left(T^{1}_{\text{authuttle10}} + T^{1}_{\text{authuttle10}} \right) * \left(\widetilde{GC}^{0}_{\text{synthetic\_autshuttle10}} - \left(\bar{w}^{1}_{\text{vkm\_autshuttle10}} + p^{1}_{\text{vkm\_public}} + \left(\left(\bar{\alpha}_{\text{int\_crash\_autshuttle10}} * c^{1}_{\text{crash\_vkm\_autshuttle10}} \right) / 2 \right) \right) \right) \right]$$

Thus $T^{o}_{\text{autshuttle10}} = 0$, but we apply vkm from the policy scenario ($T^{1}_{\text{authuttle10}}$). Subsequently, $GC^{o}_{\text{autshuttle10}} = 0$, but we apply the synthetic generalised cost ($\widetilde{GC}^{0}_{\text{synthetic\_autshuttle10}}$), as explained in section 3.2.1 (Table 3.1).

For automated on-demand shuttle buses, e.g., the 8-seat capacity type, we can estimate the following consumer surplus change:

$$\Delta CS_{\text{autshuttle8}} = {}^{1}\!/_{2}\left[\left(T^{1}_{\text{authuttle8}} + T^{1}_{\text{authuttle8}}\right) * \left(\widetilde{GC}^{0}_{\text{synthetic\_autshuttle8}} - \left(\overline{w}^{1}_{\text{vkm\_autshuttle8}} + p^{1}_{\text{vkm\_autshuttle8}} * n_{\text{occ\_autshuttle8}} + \left(\left(\overline{\alpha}_{\text{int\_crash\_autshuttle8}} * c^{1}_{\text{crash\_vkm\_autshuttle8}}\right)/_{2}\right)\right)\right)\right]$$

The expression is exactly the same for the 15-seat capacity type.

For automated ride-sharing passenger cars (shared taxis), we can estimate the following consumer surplus change:

$$\Delta CS_{\text{autcartaxi}} = {}^{1}\!/_{2}\left[\left(T^{1}_{\text{autcartaxi}} + T^{1}_{\text{autcartaxi}}\right) * \left(\widetilde{GC}^{0}_{\text{synthetic\_autcartaxi}} - \left(\overline{w}^{1}_{\text{vkm\_autcartaxi}} + p^{1}_{\text{vkm\_autcartaxi}} * n_{\text{occ\_autcartaxi}} + \left(\left(\overline{\alpha}_{\text{int\_crash\_autcar}} * c^{1}_{\text{crash\_vkm\_autcar}}\right)/_{2}\right)\right)\right)\right]$$

As stated above, these transport modes are only activated under the specific sub-use case implementation; AUSS policy scenario or policy scenario involving automated ride sharing.

Active transport users

Travel time change and valuation of travel time savings

As for other transport modes, we apply the travel-purpose-weighted estimate of VTTS/hour for active travel (from Table 2.10). This estimate is a vkm-weighted average of VTTS: $w_{\text{hour\_active}} = \left(s_{\text{vkm\_active\_cycle}} * w_{\text{hour\_cycle}}\right) + \left(\left(1 - s_{\text{vkm\_active\_cycle}}\right) * w_{\text{hour\_walk}}\right)$, for the share of cyclists and the share of pedestrians. As a default, we have applied a 50-50 distribution of cycle and walk pkm in active transport, but that might be relevant to adjust for the PST/CBA user. Furthermore, we disregarded congestion for cycling and walking, thus applying a common VTTS that represents free-flow VTTS (Table 3.5).

Table 3.5: Valuation of travel time savings for active transport, weighted by travel purpose, EU-28 - GDP/capita in EUR2020 (*30,500*)

	Cyclist	Pedestrian	Active traveller
	50%	*50%*	*100%*
VTTS (€/hour)	*10,43*	*12,05*	*11,24*
Multiplicator	*1,16*	*1,34*	

Source: Table 2.10, with only rounding error differences.

VTTS/hour is transferred to VTTS/pkm, applying the travel time. Also the travel time for active transport is a vkm-weighted average of the travel time by cycle (default of 15 km/h and hence 4 min/km) and on foot (default of 5 km/h and hence 12 min/km), thus: $h_{\text{min\_km\_active}} = s_{\text{vkm\_active\_cycle}} * h_{\text{min\_km\_cycle}} + \left(1 - s_{\text{vkm\_active\_cycle}}\right) * h_{\text{min\_km\_walk}}$. For 50-50 pkm shares the weighted average travel time ($h_{\text{min\_km\_active}}$) is (10 km/h and) 6 min/km. The VTTS/pkm is then:

$$w_{\text{pkm\_active}} = \frac{w_{\text{hour\_active}}}{60} * h_{\text{min\_km\_active}}$$

For active transport, the VTTS/vkm is equal to VTTS/pkm, assuming the occupancy ($n_{\text{occ\_active}}$) is 1:

$$w_{\text{vkm\_active}} = n_{\text{occ\_active}} * w_{\text{pkm\_active}}$$

It is the VTTS/vkm ($w_{\text{vkm\_active}}$) that enters the estimated generalised costs (GC) for active transport "consumers", respectively under baseline (0) and policy scenario (1).[96]

Vehicle operating and ownership costs (voc)
The voc is included in the generalised costs for people cycling or walking. As indicated in 2.2.1 and 3.2.1, we disregard voc for walking, while for cycling it is set to about 20% of the voc for manual cars. Then the weighted voc for active transport is about 10% of the voc for manual cars:

$$c_{\text{voc\_vkm\_active}} = s_{\text{vkm\_active\_cycle}} * \left(0.2 * c_{\text{voc\_vkm\_mancar}}\right) + \left(1 - s_{\text{vkm\_active\_cycle}}\right) * 0$$

The voc/vkm ($c_{\text{voc\_vkm\_active}}$) enters the estimated generalised costs (GC) for active transport users, respectively, under the baseline scenario (0) and the policy scenario (1).[97]

Internal costs of crashes (fatality, injury, material damage)
Active transport is always included among the transport modes for modal crash cost estimation. The attributed relative crash cost contribution ($\bar{\theta}_{\text{crash\_active}}$) is shown in Table 2.22. The formulas for deriving the crash cost per vkm ($c_{\text{crash\_vkm\_active}}$), internal plus external, are shown in sections 2.2.3 and 3.2.1. The (annual) crash costs allocated to active transport will then be:

$$C_{\text{crash\_active}} = \tilde{C}_{\text{crash\_active}} * \left(\frac{n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}}{\tilde{C}_{\text{crash\_active}} + \cdots + \tilde{C}_{\text{crash\_mode5}}}\right)$$

The term $\tilde{C}_{\text{crash\_active}} = \left(\left(n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}\right) * \left(\frac{T_{\text{active}}}{T_{\text{safety}}}\right) * \bar{\theta}_{\text{crash\_active}}\right)$ is the unscaled allocated share of crash cost to active transport based on its relative crash cost rate ($\bar{\theta}_{\text{crash\_active}}$); the unscaled costs of other modes within are summed in the denominators of the expression for $C_{\text{crash\_active}}$.

For active transport, the external share ($\bar{\alpha}_{\text{ext\_crash\_active}}$) is set to 30% (Table 2.22); thus the internal ($1 - \bar{\alpha}_{\text{ext\_crash\_active}}$) is 70%. Thus, the internal crash cost per vkm for active transport users is then:

$$c_{\text{crash\_int\_vkm\_active}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_active}}\right) * \frac{C_{\text{crash\_active}}}{T_{\text{active}}}$$

[96] Annual VTTS for active travellers is: $W_{\text{active}} = w_{\text{vkm\_active}} * T_{\text{active}}$.

[97] The annual voc will be: $C_{\text{voc\_active}} = c_{\text{voc\_vkm\_active}} * T_{\text{active}}$.

This is the cost element for active travellers that enters the estimated generalised costs (GC), respectively under the baseline scenario (0) and the policy scenario (1).[98]

<u>The consumer surplus change for active transport users</u>
Summarising the three internal cost components for active travellers, we can estimate the following consumer surplus change:

$$\Delta CS_{\text{active}} = {}^{1}/_{2}\left[\left(T^{0}_{\text{active}} + T^{1}_{\text{active}}\right) * \left(\left(w^{0}_{\text{vkm\_active}} + c^{0}_{\text{voc\_vkm\_car}} + \left(\bar{\alpha}_{\text{int\_crash\_active}} * c^{0}_{\text{crash\_vkm\_active}}\right)\right) - \left(w^{1}_{\text{vkm\_active}} + c^{1}_{\text{voc\_vkm\_active}} + \left(\bar{\alpha}_{\text{int\_crash\_active}} * c^{1}_{\text{crash\_vkm\_active}}\right)\right)\right)\right]$$

Thus, $GC^{0}_{\text{active}} = \left(w^{0}_{\text{vkm\_active}} + c^{0}_{\text{voc\_vkm\_active}} + \left(\bar{\alpha}_{\text{int\_crash\_active}} * c^{0}_{\text{crash\_vkm\_active}}\right)\right)$, and vice versa for GC^{1}_{active} (and $\bar{\alpha}_{\text{int\_crash\_active}} = 1 - \bar{\alpha}_{\text{ext\_crash\_active}}$).

3.3 Producer surplus changes for transport service providers

3.3.1 Simplified estimation of change in producer surplus

General formula
The handling of impacts on public transport service providers (including those providing automated shuttles) and freight providers will be based on a simplified estimation of producer surplus change.

For public transport and taxi providers, a general formula can be stated in the following way: $PS = (p - c) * T$, where p is price per service unit, in this case, price per km (it could also be price per pkm or price per trip), c is unit costs, and T is the transport service quantity (vkm). The relevant measures in the CBA module is not the p and c, as such, but the change in the producer surplus, ΔPS, from baseline scenario to policy scenario, i.e.:

$$\Delta PS_{\text{public}} = \left(\left(p^{1}_{\text{vkm\_public}} - c^{1}_{\text{vkm\_public}}\right) * T^{1}_{\text{public}}\right) - \left(\left(p^{0}_{\text{vkm\_public}} - c^{0}_{\text{vkm\_public}}\right) * T^{0}_{\text{public}}\right)$$

Even if our estimates of the p and c might be imprecise in absolute terms, the change in surplus between policy and baseline will follow the differences that stem from the PST.

For freight service suppliers we disregard the selling price per unit for the freight service provider, as we lack information about these figures. Then only the costs for the freight transport providers vary between the baseline scenario and the policy scenario:

$$\Delta PS_{\text{freight}} = \left(-c^{1}_{\text{vkm\_freight}} * T^{1}_{\text{freight}}\right) - \left(-c^{0}_{\text{vkm\_freight}} * T^{0}_{\text{freight}}\right)$$

In the case of freight transport, we build on unit cost estimates from the PST, although these cover only the relevant LCV part in the SUC; we have added default unit costs for

[98] Annual internal crash costs are: $C_{\text{crash\_int\_active}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_active}}\right) * C_{\text{crash\_active}}$.

HGV; as well as assuming that all other freight can be described by the same unit costs. Thus, our estimated c might be imprecise in absolute terms, but the change in surplus between policy and baseline will still follow the differences that stem from the PST.

The elements of prices and costs

Collected fares, transport service providers

The collected payments per vkm for transport service providers (public transport and taxi) are equal to the payments per vkm by the users, the transport service consumers. The unit price per vkm is the p in the producer surplus expression – for public transport and taxi service providers.

Vehicle operating and ownership costs, transport service providers

The voc for public transport and taxi providers has a point of departure in the voc for (private) passenger cars. The voc for cars is given from the PST variable *vehicle operating cost*, a weighted voc for manual and automated cars; the automated having a voc that is 67% of the voc of manual. Based on default estimates of voc for all included transport modes (Table 2.14), multipliers (ω_{voc}) have been derived for other transport modes than passenger cars. Thus, for an automated shuttle with 8 seats, we have that: $c_{\mathrm{voc\_vkm\_autshuttle8}} = c_{\mathrm{voc\_vkm\_autcar}} * \omega_{\mathrm{voc\_autshuttle8}}$; and similarly for other automated shuttles; and we apply: $c_{\mathrm{voc\_withpers\_vkm\_public}} = c_{\mathrm{voc\_vkm\_mancar}} * \omega_{\mathrm{voc\_withpers\_public}}$ for (manual) public transport. The applied multipliers for the automated shuttles are, respectively for 8- 15- and 10-seat capacity: 1.36, 1.78, 1.58; and for the (weighted average) public transport the multiplier is 9.03. For automated ride-sharing taxis, we assume the same voc as for automated cars in general.[99]

For freight transport scenarios, there is no voc provided from the PST, but the CBA module applies the voc based on Hu et al. (2021a, Table 4.3). The voc estimates for different freight vehicles, applied in the CBA, are listed in Table 2.32. What is provided from the PST is the general *freight transport cost* per tkm. We apply this PST variable only for setting the growth in the voc estimates (e.g., for automated LCV under the automated delivery policy scenario, $c^{\mathrm{aut\_delivery}}_{\mathrm{voc\_withpers\_vkm\_autLCV}}$).

The voc is a main part of the unit cost per vkm, the c in the producer surplus expression.

Internal crash costs, transport service providers

For public transport beyond AUSS there is no inclusion of internal crash costs (as these are not included in the PST). For AUSS point-to-point, AUSS on-demand, and for automated ride-sharing service providers, the foundation is described in the section above (section 3.2.1), as well as in section 2.2.3; it builds on the same transport mode crash cost base as that for transport consumers. We assume that for AUSS and ride-

[99] The average voc/vkm, disregarding personnel costs, might very well be lower for automated ride-sharing taxis than for automated cars in general, due to an expected higher annual mileage. However, some monitoring personnel might also be involved under the automated ride sharing, as well as under the AUSS; thus, the personnel costs might not be zero, although far lower than personnel costs in manual taxi service or manual bus transport.

sharing taxis, the transport service providers assume half of the internal crash costs per vkm (while the passengers assume the other half).[100]

For freight transport, the attribution of total crash costs to freight vehicles follow exactly the same approach as for other included transport modes (section 2.2.3).[101] For freight vehicles, the service provider assumes all internal crash costs.

The internal crash costs for the transport service providers represent a part of the unit cost per vkm, the c in the producer surplus expression.

<u>Summarising price and cost elements, transport service providers</u>
What enters the p for public transport and taxi service providers is the collection of fares or tickets per vkm; that just mirrors the payments by consumer, with the opposite sign ($p_{\text{vkm\_mode}}$).

What enters the c for manual public transport is the voc (e.g., $c_{\text{voc\_withpers\_vkm\_public}}$). For AUSS and automated ride-sharing providers, there is also an internal crash cost (e.g., $c_{\text{crash\_int\_vkm\_autshuttle\_prov}} = c_{\text{crash\_int\_vkm\_autshuttle}}/2$). What enters the c for freight transport providers is also a voc (e.g., $c^{\text{aut\_delivery}}_{\text{voc\_withpers\_vkm\_autLCV}}$) and an internal crash cost (e.g., $c_{\text{crash\_int\_vkm\_autLCV}}$).

3.3.2 Details on producer surplus changes for transport mode service providers

Public transport providers (beyond AUSS)
<u>Ticket sales (individual single-trip tickets)</u>
The ticket sales of the public transport operator mirror (exactly) the ticket costs of the public transport users; it is the same size with opposite sign. Thus, the ticket sale income per vkm for public transport providers will be:

$$p_{\text{vkm\_public}} = \left(\bar{p}_{\text{public\_trip}} * \left(Q_{\text{public}}/\bar{T}_{\text{trip}}\right)\right) \Big/ \left(Q_{\text{public}}/n_{\text{occ\_public}}\right) = P_{\text{public}} \Big/ T_{\text{public}}$$

That is, the ticket income per vkm equals the annual collected payment (trip price times annual trips) divided by public transport annual vkm (public transport pkm divided by occupancy).

<u>Vehicle operating and ownership costs (voc)</u>
The voc for public transport providers has a point of departure in the voc for (private) manual passenger cars; the voc for cars is given from the PST variable *vehicle operating cost*, a weighted voc for manual and automated cars; the automated having a voc that is

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[100] Crash costs attributed to AUSS and automated ride-sharing cars are only included under passenger transport scenarios ($T_{\text{safety\_passenger}}$), when these SUCs are implemented. As specified in sections 2.2.3 and 3.2.1, $T_{\text{safety\_passenger}} = (T_{\text{autcar}} + T_{\text{mancar}} + T_{\text{active}} + T_{\text{autshuttle}})$. Automated cars are also included among the transport modes under freight transport scenarios, but not automated ride-sharing taxi cars.

[101] Crash costs attributed to freight transport are only included under freight transport scenarios ($T_{\text{safety\_freight}}$). As specified in sections 2.2.3 and 3.2.1, $T_{\text{safety\_freight}} = \left(T_{\text{autfreight}} + T_{\text{manfreight}} + T_{\text{autcar}} + T_{\text{mancar}} + T_{\text{active}}\right)$.

67% of the voc of manual. Based on default estimates of voc for all included transport modes, multipliers (ω_{voc}) have been derived for other transport modes than passenger cars. The voc multiplier for the vkm-weighted public transport of rail-based (with vkm share: $s_{\text{vkm\_public\_rail}} = \frac{T_{\text{rail}}}{T_{\text{public}}}$) and bus-based (with vkm share: $s_{\text{vkm\_public\_manbus}} = \frac{T_{\text{manbus}}}{T_{\text{public}}}$) is given as:

$$\omega_{\text{voc\_withpers\_public}} = \left(\omega_{\text{voc\_withpers\_rail}} * {T_{\text{rail}}}/{T_{\text{public}}}\right) + \left(\omega_{\text{voc\_withpers\_manbus}} * {T_{\text{manbus}}}/{T_{\text{public}}}\right)$$ [102]

Thus, the voc/vkm for public transport operators is derived by:

$$c_{\text{voc\_withpers\_vkm\_public}} = \omega_{\text{voc\_withpers\_public}} * c_{\text{voc\_vkm\_mancar}}$$

This is what enters the estimated costs (c) for public transport providers, respectively, under the baseline scenario (0) and the policy scenario (1).

Internal costs of crashes (primarily material damage)
Public transport (beyond AUSS) is not included among the transport modes underlying the PST variable *road safety total effect*. Thus there is no content for $C_{\text{crash\_public}}$ and $C_{\text{crash\_int\_public}}$; these are zero for public transport in the baseline as well as policy scenarios.

The producer surplus change for public transport providers
The applied formula for producer surplus is: $PS = (p - c) * T$, where p is price per vkm (derived from individual single-trip payments) and c is cost per vkm for the service provision. In the case of public transport, what is included is estimated ticket sales and estimated voc. It is the change in producer surplus, from baseline scenario to policy scenario, that we estimate, i.e.:

$$\Delta PS_{\text{public}} = \left(\left(p^1_{\text{vkm\_public}} - c^1_{\text{voc\_withpers\_vkm\_public}}\right) * T^1_{\text{public}}\right) - \left(\left(p^0_{\text{vkm\_public}} - c^0_{\text{voc\_withpers\_vkm\_public}}\right) * T^0_{\text{public}}\right)$$

AUSS providers plus ride-sharing taxi providers
Ticket sales and taxi-ride sales
The ticket sales of point-to-point AUSS operators mirror the ticket costs of the AUSS point-to-point users; it is the same size with opposite sign:

$$p_{\text{vkm\_autshuttle10}} = {\left(\bar{p}_{\text{public\_trip}} * \left(Q_{\text{autshuttle10}}/\bar{T}_{\text{trip\_autshuttle10}}\right)\right)}\Big/{\left(Q_{\text{autshuttle10}}/n_{\text{occ\_autshuttle10}}\right)} = {P_{\text{autshuttle10}}}/{T_{\text{autshuttle10}}}$$

That is, the annual collected payment (trip price times annual trips) divided by point-to-point AUSS annual vkm (point-to-point AUSS pkm divided by occupancy).

The general trip length in the CBA module is $\bar{T}_{\text{trip}} = \bar{T}_{\text{trip\_commute}}$, the commuting single trip derived from the PST variable *commuting distances*; but for AUSS specific trip lengths are provided (Table 2.26); in general $\bar{T}_{\text{trip\_autshuttle}} < \bar{T}_{\text{trip}}$.

[102] The shares of the main types of public transport (and their occupancy levels) can be adjusted by the PST/CBA user. For the defaults applied in this deliverable, $\omega_{\text{voc\_withpers\_manbus}} = 5.72$.

For automated on-demand AUSS and automated ride-sharing providers, the taxi-ride sales will mirror the taxi costs of the users, e.g.:

$$p_{\text{vkm\_autshuttle8}} = {\left(\bar{p}_{\text{taxi\_pkm}} * Q_{\text{autshuttle8}}\right)}/{\left(Q_{\text{autshuttle8}}/n_{\text{occ\_autshuttle8}}\right)} = {P_{\text{autshuttle8}}}/{T_{\text{autshuttle8}}}$$

That is, the annual collected payment (fare per pkm times annual pkm) divided by annual vkm (pkm divided by occupancy). The same formula applies to 15-seat on-demand AUSS and automated ride-sharing cars.

Vehicle operating and ownership costs (voc)

The voc for automated shuttles has a point of departure in the PST variable *vehicle operating cost*, the weighted voc for manual and automated cars; the automated having a voc that is 67% of the voc of manual. The voc for AUSS is derived by use of the voc for automated cars with multipliers (ω_{voc}). The voc/vkm for, e.g., the 8-seat AUSS, is derived by:

$$c_{\text{voc\_vkm\_autshuttle8}} = \omega_{\text{voc\_autshuttle8}} * c_{\text{voc\_vkm\_autcar}}$$

The expression is the same for 15-seat and 10-seat shuttles; for automated ride-sharing cars the voc/vkm is equal to that for automated private cars. The multipliers vary slightly between the shuttle sizes (Table 2.14: $\omega_{\text{voc\_autshuttle8}} = 2.06$, $\omega_{\text{voc\_autshuttle10}} = 2.61$, $\omega_{\text{voc\_autshuttle15}} = 1.19$, and $\omega_{\text{voc\_autcartaxi}} = 1$). The relatively higher voc/vkm for on-demand AUSS than for point-to-point AUSS is due to relatively lower mileage for on-demand AUSS (Table 2.26). Notwithstanding, the sizes of multipliers for automated shuttles (with respect to automated private cars) are relatively lower than for manual buses (with respect to manual private cars), as there are no driver costs; and we disregard monitoring personnel costs.

Internal costs of crashes (primarily material damage)

The foundation for crash costs for automated shuttle and automated ride-sharing taxi providers is the same as for the AUSS and taxi consumers; the providers assume the other half of the internal crash costs per vkm:

$$c_{\text{crash\_int\_vkm\_autshuttle\_prov}} = {c_{\text{crash\_int\_vkm\_autshuttle}}}/{2} = {\left(\left(1 - \bar{\alpha}_{\text{ext\_crash\_autshuttle}}\right) * c_{\text{crash\_vkm\_autshuttle}}\right)}/{2}$$

This applies to all types of AUSS providers and the automated ride-sharing passenger car provider.

The producer surplus change for AUSS and automated ride-sharing providers

In the case of AUSS and ride-sharing taxis, what is included is estimated ticket sales or taxi-ride sales and the estimated voc and the internal (provider share of) crash costs. It is the change in producer surplus, from baseline scenario to policy scenario, that we estimate, e.g.:

$$\Delta PS_{\text{autshuttle8}} = \left(\left(p^1_{\text{vkm\_autshuttle8}} - c^1_{\text{vkm\_autshuttle8}} - \left({\left(\bar{\alpha}_{\text{int\_crash\_autshuttle8}} * c^1_{\text{crash\_autshuttle8}}\right)}/{2}\right)\right) * T^1_{\text{autshuttle8}}\right) - 0$$

This function is applied for all types of AUSS providers and for the the automated ride-sharing passenger car provider.

Freight transport service providers

Vehicle operating and ownership costs (voc)

The voc/vkm for LCV is based on Hu et al. (2021a), while voc/vkm for HGV is derived by multiplying LCV annual cost levels by three; the weighted averages of manual and automated freight vehicles also follow from relative loads and relative shares of tkm and vkm (Table 2.14, Table 2.32).[103]

Under the specific freight SUCs, there is more variation in voc/vkm than just LCV vs. HGV and automated vs. manual; there are semi-automated LCV and there are additional combinations of automated and manual LCV (automated night delivery, and manual and automated consolidation) that yield additional voc/vkm estimates.

There are six different voc/vkm for LCV within freight SUCs (Table 2.32): $c^{\text{man\_delivery}}_{\text{voc\_withpers\_vkm\_manLCV}}$, $c^{\text{aut\_delivery}}_{\text{voc\_withpers\_vkm\_autLCV}}$, $c^{\text{aut\_night\_delivery}}_{\text{voc\_withpers\_vkm\_autLCV}}$, $c^{\text{semiaut\_night\_delivery}}_{\text{voc\_withpers\_vkm\_autLCV}}$, $c^{\text{man\_consolidation}}_{\text{voc\_withpers\_vkm\_manLCV}}$, and $c^{\text{aut\_consolidation}}_{\text{voc\_withpers\_vkm\_autLCV}}$.

For HGV there is only a manual vs. automated variation in voc/vkm: $c^{\text{aut\_consolidation}}_{\text{voc\_withpers\_vkm\_autHGV}}$, and $c^{\text{man\_consolidation}}_{\text{voc\_withpers\_vkm\_manHGV}} = c^{\text{man\_origindest}}_{\text{voc\_withpers\_vkm\_manHGV}}$; but for the hub-to-hub policy scenario, a vkm-weighted average of automated and manual HGV voc/vkm is applied:

$$c^{\text{hub\_to\_hub}}_{\text{voc\_withpers\_vkm\_HGV}} = \left(\left(s_{\text{hub\_to\_hub\_aut\_HGV}} * c^{\text{aut\_consolidation}}_{\text{voc\_withpers\_vkm\_autHGV}}\right) + \left(\left(1 - s_{\text{hub\_to\_hub\_aut\_HGV}}\right) * c^{\text{man\_consolidation}}_{\text{voc\_withpers\_vkm\_manHGV}}\right)\right)$$

A 50-50 share of automated and manual HGV is default in the hub-to-hub policy scenario.

Regarding the non-SUC freight, only manual delivery and automated delivery set the voc/vkm for LCV:

$$c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_manLCV}} = c^{\text{man\_delivery}}_{\text{voc\_withpers\_vkm\_manLCV}}$$

and

$$c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_autLCV}} = c^{\text{aut\_delivery}}_{\text{voc\_withpers\_vkm\_autLCV}}$$

For non-SUC HGV, the voc/vkm equals the voc/vkm for manual and automated HGV in the SUC:

$$c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_manHGV}} = c^{\text{man\_consolidation}}_{\text{voc\_withpers\_vkm\_manHGV}}$$

and

$$c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_autHGV}} = c^{\text{aut\_consolidation}}_{\text{voc\_withpers\_vkm\_autHGV}}$$

The CBA module carries out the major calculations for vkm-weighted averages of automated freight vehicles (LCV and HGV), and vkm-weighted averages of manual freight vehicles (LCV and HGV). Thus:

$$c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_manfreight}} = \left(\left(s^{\text{NONSUC}}_{\text{freight\_LCV}} * c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_manLCV}}\right) + \left(\left(1 - s^{\text{NONSUC}}_{\text{freight\_LCV}}\right) * c^{\text{NONSUC}}_{\text{voc\_withpers\_vkm\_manHGV}}\right)\right)$$

and

[103] The weighted voc/vkm averages of freight vehicles (LCV plus HGV) are based on the following: the default relative load capacity of HGV vs. LCV is set to 9-1 and the shares of tkm transported are equal between HGV and LCV (50%-50%); that yields 90% of vkm by LCV versus 10% by HGV.

$$c_{\text{voc\_withpers\_vkm\_autfreight}}^{\text{NONSUC}} = \left(\left(s_{\text{freight\_LCV}}^{\text{NONSUC}} * c_{\text{voc\_withpers\_vkm\_autLCV}}^{\text{NONSUC}}\right) + \left(\left(1 - s_{\text{freight\_LCV}}^{\text{NONSUC}}\right) * c_{\text{voc\_withpers\_vkm\_autHGV}}^{\text{NONSUC}}\right)\right)$$

These non-SUC freight components will be consistent between baseline and policy scenario. These are the voc elements for freight vehicles that enters the overall estimated costs, c, respectively under the baseline scenario (0) and the policy scenario (1).

The relative shares of automated versus manual freight vehicles are decided by the MPR for freight in the PST (Table 2.1). The additional SUC freight component might comprise any combination freight vehicles and will always differ between baseline scenario and policy scenario.

As clarified above (and in section 2.4.4), the PST variable *freight transport cost* is applied for setting the growth of all freight vehicle voc/vkm.

Internal congestion costs

For freight transport providers, we include an estimate of internal congestion costs, $c_{\text{int\_cong\_vkm\_freight}} = c_{\text{voc\_withpers\_vkm\_freight}} - c_{\text{voc\_nopers\_vkm\_freight}}$; based on primarily the appointment costs (Table 2.13). The internal congestion cost for freight can be set as fixed shares of the voc/vkm:

$$c_{\text{int\_cong\_vkm\_freight}} = c_{\text{voc\_withpers\_vkm\_freight}} * \omega_{\text{int\_cong\_vkm\_freight}}$$

The multiplier ($\omega_{\text{int\_cong\_vkm\_freight}}$) will be higher for manual than for automated, and higher for LCV than for HGV. For manual LCV and semi-automated LCV the congestion the multiplier is 85%, while it is 61% for manual HGV. For automated freight vehicles the multipliers are 71% and 28%, respectively for LCV and HGV; the weighted averages are 83% for manual and 67% for automated freight vehicles.

Thus, as the CBA module carries out the major calculations for weighted averages of automated freight vehicles (LCV and HGV), and weighted averages of manual freight vehicles (LCV and HGV), we have:

$$c_{\text{int\_cong\_vkm\_manfreight}}^{\text{NONSUC}} = \left(\left(s_{\text{freight\_LCV}}^{\text{NONSUC}} * c_{\text{voc\_withpers\_vkm\_manLCV}}^{\text{NONSUC}} * 0.85\right) + \left(\left(1 - s_{\text{freight\_LCV}}^{\text{NONSUC}}\right) * c_{\text{voc\_withpers\_vkm\_manHGV}}^{\text{NONSUC}} * 0.61\right)\right)$$

which yields $c_{\text{int\_cong\_vkm\_manfreight}}^{\text{NONSUC}} = \left(c_{\text{voc\_withpers\_vkm\_manfreight}}^{\text{NONSUC}} * 0.83\right)$, when $s_{\text{freight\_LCV}}^{\text{NONSUC}} = 90\%$; and

$$c_{\text{int\_cong\_vkm\_autfreight}}^{\text{NONSUC}} = \left(\left(s_{\text{freight\_LCV}}^{\text{NONSUC}} * c_{\text{voc\_withpers\_vkm\_autLCV}}^{\text{NONSUC}} * 0.71\right) + \left(\left(1 - s_{\text{freight\_LCV}}^{\text{NONSUC}}\right) * c_{\text{voc\_withpers\_vkm\_autHGV}}^{\text{NONSUC}} * 0.28\right)\right)$$

which yields $c_{\text{int\_cong\_vkm\_autfreight}}^{\text{NONSUC}} = \left(c_{\text{voc\_withpers\_vkm\_autfreight}}^{\text{NONSUC}} * 0.67\right)$, when $s_{\text{freight\_LCV}}^{\text{NONSUC}} = 90\%$.

These are the internal congestion cost elements for freight vehicles that enters the overall estimated costs, c, respectively under the baseline scenario (0) and the policy scenario (1).

These non-SUC freight components will be consistent between baseline and policy scenario.

The SUC-freight part will vary between baseline and policy; and vary according to the specific SUC.

The internal congestion cost is applied to the share of freight travel time in congestion; respectively, $k_{\text{traveltime\_cong\_manfreight}}$ and $k_{\text{traveltime\_cong\_autfreight}}$.

Internal costs of crashes (primarily material damage)

Crash costs attributed to freight transport are only included under freight transport scenarios ($T_{\text{safety\_freight}}$).[104] These freight vkm comprise both SUC-freight and non-SUC freight. The (annual) crash costs allocated to the vkm-weighted LCV-HGV averages of respectively automated and manual freight vehicles are:

$$C_{\text{crash\_autfreight}} = \tilde{C}_{\text{crash\_autfreight}} * \left(\frac{n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety\_freight}}}{\tilde{C}_{\text{crash\_autfreight}} + \cdots + \tilde{C}_{\text{crash\_mode5}}} \right)$$

and, similarly, for manual freight vehicles:

$$C_{\text{crash\_manfreight}} = \tilde{C}_{\text{crash\_manfreight}} * \left(\frac{n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety\_freight}}}{\tilde{C}_{\text{crash\_manfreight}} + \cdots + \tilde{C}_{\text{crash\_mode5}}} \right)$$

The term $\tilde{C}_{\text{crash\_mode}} = \left(\left(n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety\_freight}} \right) * \left(\frac{T_{\text{mode}}}{T_{\text{safety\_freight}}} \right) * \bar{\theta}_{\text{crash\_mode}} \right)$ is the unscaled allocated share of crash cost to the specific mode based on its relative crash cost rate ($\bar{\theta}_{\text{crash\_mode}}$); the unscaled costs of other modes within are summed in the denominators of the expressions for $C_{\text{crash\_autfreight}}$ and $C_{\text{crash\_manfreight}}$. As indicated, the crash cost rate differs between LCV and HGV, as well as differing between manual and automated.

The attributed crash cost per vkm for automated cars is then just:

$$c_{\text{crash\_vkm\_autfreight}} = \frac{C_{\text{crash\_autfreight}}}{T_{\text{autfreight}}}$$

and

$$c_{\text{crash\_vkm\_manfreight}} = \frac{C_{\text{crash\_manfreight}}}{T_{\text{manfreight}}}$$

The crash costs allocated to transport modes have different shares of external and internal parts (see Table 2.22). For freight vehicles, the external share ($\bar{\alpha}_{\text{ext\_crash\_freight}}$) is set to 70%; thus the internal $(1 - \bar{\alpha}_{\text{ext\_crash\_freight}})$ is 30%; with no differentiation between manual and automated. Thus, the internal crash cost per vkm for automated freight vehicles is then:

$$c_{\text{crash\_int\_vkm\_autfreight}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_freight}}\right) * \frac{C_{\text{crash\_autfreight}}}{T_{\text{autfreight}}}$$

and

$$c_{\text{crash\_int\_vkm\_manfreight}} = \left(1 - \bar{\alpha}_{\text{ext\_crash\_freight}}\right) * \frac{C_{\text{crash\_manfreight}}}{T_{\text{manfreight}}}$$

These are the crash cost elements for freight vehicles that enters the overall estimated costs, c, respectively under the baseline scenario (0) and the policy scenario (1).

The producer surplus change for freight transport providers

[104] As clarified in sections 2.2.3 and 3.2.1, $T_{\text{safety\_freight}} = \left(T_{\text{autfreight}} + T_{\text{manfreight}} + T_{\text{autcar}} + T_{\text{mancar}} + T_{\text{active}}\right)$.

In the case of freight vehicles, what is included is the estimated voc, internal congestion costs, and internal crash costs. It is the change in producer surplus, from baseline scenario to policy scenario, that we estimate, e.g., fro manual freight vehicles:

$$\Delta PS_{\text{manfreight}} = \left(\left(-c^{1}_{\text{voc\_withpers\_vkm\_manfreight}} - \left(c^{1}_{\text{int\_cong\_vkm\_manfreigh}} * k_{\text{traveltime\_cong\_manfreight}}\right) - c^{1}_{\text{crash\_int\_vkm\_manfreight}}\right) * T^{1}_{\text{manfreight}}\right) - \left(\left(-c^{0}_{\text{voc\_withpers\_vkm\_manfreight}} - \left(c^{0}_{\text{int\_cong\_vkm\_manfreigh}} * k_{\text{traveltime\_cong\_manfreight}}\right) - c^{0}_{\text{crash\_int\_vkm\_manfreight}}\right) * T^{0}_{\text{manfreight}}\right)$$

An equivalent expression is applied for automated freight vehicles.

3.4 Monetised external effects (external costs)

3.4.1 Three types of external effects from the PST

External costs are all the monetised impacts of infrastructure use that affect other persons, other infrastructure users or the remaining society. The monetised external effects, based on available PST variables, comprise emissions of local air pollutants, NO_X and PM_{10}, and of greenhouse gases (CO_2 equivalents), as well as crashes and congestion.

For crashes and emissions, the PST yields an average impact, the crashes ($n^{\text{crash/vkm}}$) and emission per vkm ($\overline{\text{emission}}^{\text{g/vkm}}$). Setting an average valuation of a crash and a gram of NO_X, PM_{10}, and CO_2, we can derive the total costs produced by the transport activity (in reference/baseline and with implemented policy). For emissions the total cost will then be equal to: $\overline{\text{emission}}^{\text{g/vkm}} * c^{\text{g}}_{\text{emission}} * T_{\text{emission}}$, with different costs for NO_X, PM_{10}, and CO_2; and a smaller set of transport modes contributing to CO_2 emissions (sum over vkm equal to $T_{\text{emission\_global}}$) , compared to emission of NO_X, PM_{10} (sum over vkm equal to $T_{\text{emission\_local}}$). For crashes total cost is: $n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}$; different sets of transport modes enter under passenger transport scenarios vs. freight transport scenarios ($T_{\text{safety\_passenger}}$ vs. $T_{\text{safety\_freight}}$). For congestion, an average valuation of the social (external) impact is not directly available; what is available is the (average) external congestion cost per vkm per transport mode: $c_{\text{ext\_cong\_vkm\_mode}}$.; and we limit the scope of the external congestion cost to the fixed share of vkm under congestion ($k_{\text{vkm\_cong}} = 0.25$).

We have opted for a common approach of deriving what each transport mode on average "produces" in external emission costs, external crash costs, and external congestion costs, per vkm. For crashes and emission, we apply the relative emission cost and relative crash cost per transport mode: $\bar{\theta}_{\text{crash\_mode}}$ and $\bar{\theta}_{\text{emission\_mode}}$, to derive the external cost per mode. We scale these estimates to the total cost estimates, for emissions and crashes, such that the estimates per transport mode will sum to the total cost that we can derive directly by multiplying the PST variables (*NO_X / PM_{10} / CO_2 due to vehicles*, and *road safety total effect*) by the total vkm of all included transport and the average valuations per unit.

Furthermore, for crashes and congestion there is an external part (what the traveller inflicts on others) and an internal part (what the traveller inflicts on himself/herself). For crashes, the external and internal part are derived together and then divided into specified shares that differ across modes ($\bar{\alpha}_{\text{ext\_crash\_mode}}$ and $1 - \bar{\alpha}_{\text{ext\_crash\_mode}}$). For congestion, the external part ($c_{\text{ext\_cong\_vkm\_mode}}$) is derived from another source than the internal (the internal is based on an addendum to the VTTS under congestion).

3.4.2 Emissions – from total costs to cost entailed per transport mode

As shown in section 2.2.3, for all scenarios, the sum of emission costs for all included modes are estimated first: $\overline{\text{emission}}^{\text{g/vkm}} * c^{\text{g}}_{\text{emission}} * T_{\text{emission}}$. Then the sum is allocated to the included transport modes based on relative unit cost rates ($\bar{\theta}_{\text{emission\_mode}}$), i.e.:

$$\tilde{C}_{\text{emission\_mode1}} = \left(\left(\overline{\text{emission}}^{\text{g/vkm}} * c^{\text{g}}_{\text{emission}} * T_{\text{emission}}\right) * \left(\frac{T_{\text{mode1}}}{T_{\text{emission}}}\right) * \bar{\theta}_{\text{emission\_mode1}}\right)$$

This is then scaled to the total cost level:

$$C_{\text{emission\_mode1}} = \tilde{C}_{\text{emission\_mode1}} * \left(\frac{\overline{\text{emission}}^{\text{g/vkm}} * c^{\text{g}}_{\text{emission}} * T_{\text{emission}}}{\tilde{C}_{\text{emission\_mode1}} + \cdots + \tilde{C}_{\text{emission\_mode7}}}\right)$$

The transport modes included in these calculations, for NO_X and PM_{10}, are manual cars, automated cars, automated shuttles, (other) public transport (manual buses), manual freight, and automated freight; for CO_2 emissions, only manual cars, public transport, and manual freight are included. From the total cost share of the transport mode, we can then derive the transport mode’s cost per vkm, implicitly an “emission unit cost” for the mode:

$$c_{\text{emission\_vkm\_mode1}} = {}^{C_{\text{emission\_mode1}}}\!/_{T_{\text{mode1}}}$$ [105]

Thus, the change in the particular emission cost for the particular mode, from baseline (reference) scenario (0) to policy scenario (1), is:

$$\Delta C_{\text{emission\_mode1}} = \left(c^{1}_{\text{emission\_mode1}} * T^{1}_{\text{mode}}\right) - \left(c^{0}_{\text{emission\_mode1}} * T^{0}_{\text{mode1}}\right)$$

This external cost change is estimated for all included transport modes; and the CBA module controls that the aggregation over modes equals the initial total cost level ($\overline{\text{emission}}^{\text{g/vkm}} * c^{\text{g}}_{\text{emission}} * T_{\text{emission}}$).

3.4.3 Total crash costs, crash cost per transport mode, and external cost entailed per mode

As shown in sections 2.2.3, 3.2.2, and 3.3.2, for all scenarios the sum of crash costs for all included transport modes are estimated first: $n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}$. Then the sum is allocated to the included transport modes based on their relative unit cost levels ($\bar{\theta}_{\text{crash\_mode}}$), i.e.:

$$\tilde{C}_{\text{crash\_mode1}} = \left(\left(n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}\right) * \left(\frac{T_{\text{mode1}}}{T_{\text{safety}}}\right) * \bar{\theta}_{\text{crash\_mode1}}\right)$$

This is then scaled to the total cost level ($n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}$):

$$C_{\text{crash\_mode1}} = \tilde{C}_{\text{crash\_mode1}} * \left(\frac{n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}}}{\tilde{C}_{\text{crash\_mode1}} + \cdots + \tilde{C}_{\text{crash\_mode5}}}\right)$$

[105] The derived “unit price” for emissions of specific pollutants per vkm (or per pkm), for each transport mode, may not be exactly the same in the policy scenario as in the reference scenario, but we assume that the differences will be “small”.

The five modes in the calculations under freight transport scenarios are manual cars, automated cars, manual freight, automated freight, and active transport. Under passenger transport scenarios, only four modes are included: manual cars, automated cars, automated shuttles, and active transport (and automated shuttles are only activated under AUSS sub-use cases, not passenger car sub-use cases).

From the total cost share of the transport mode, we can then derive the transport mode's cost per vkm, implicitly a "crash unit cost" for the mode:

$$c_{\text{crash\_vkm\_mode1}} = {C_{\text{crash\_mode1}}}/{T_{\text{mode1}}}$$ [106]

Part of the crash cost that individual travellers "produce" is affecting themselves, it is "internal"; and cyclists/pedestrians, for example, will have a higher internal share than passenger cars, and cars higher than HGVs. The external crash cost per vkm is:

$$\bar{\alpha}_{\text{ext\_crash\_mode}} * c_{\text{crash\_vkm\_mode}}$$

Thus, the change in the external crash cost for a particular transport mode, from baseline (reference) scenario (0) to policy scenario (1), will be:

$$\Delta C_{\text{ext\_crash\_vkm\_mode1}} = \left(\bar{\alpha}_{\text{ext\_crash\_mode1}} * c^{1}_{\text{crash\_vkm\_mode1}} * T^{1}_{\text{mode1}}\right) - \left(\bar{\alpha}_{\text{ext\_crash\_mode1}} * c^{0}_{\text{crash\_vkm\_mode1}} * T^{0}_{\text{mode1}}\right)$$

This external cost change is estimated for all included transport modes; and the CBA module controls that the aggregation over modes equals the initial total cost level $(n^{\text{crash/vkm}} * \bar{C}_{\text{crash}} * T_{\text{safety}})$.

3.4.4 External congestion cost entailed per mode

Regarding congestion, default estimates of social congestion costs (external costs of congestion) were presented in section 2.2.2. The unit prices for each transport mode $(c_{\text{ext\_cong\_vkm\_mode}})$ are applied with the fixed 25% of vkm, and subsequently vkm, occurring under congestion. The change in the external congestion cost for a particular transport mode, from baseline scenario to policy scenario, is:

$$\Delta C_{\text{ext\_cong\_mode}} = \left(c^{1}_{\text{ext\_cong\_vkm\_mode}} * k_{\text{vkm\_cong}} * T^{1}_{\text{mode}}\right) - \left(c^{0}_{\text{ext\_cong\_vkm\_mode}} * k_{\text{vkm\_cong}} * T^{0}_{\text{mode}}\right)$$

This external cost change is estimated for all included transport modes.

3.4.5 The sum of external cost changes

The sum of external cost changes $(\Delta M_{\text{external}})$ is the change in the sum of emissions $(\Delta C_{\text{emission}})$, external crash costs $(\Delta C_{\text{ext\_crash}})$, and external congestion costs $(\Delta C_{\text{ext\_cong}})$; thus:

$$\Delta M_{\text{external}} = \Delta C_{\text{emission}} + \Delta C_{\text{ext\_crash}} + \Delta C_{\text{ext\_cong}}$$

Detailed calculations per mode, for transport consumers and service providers, are presented above (in sections 3.2.2 and 3.3.2).

[106] The derived "unit price" for crashes per vkm (or per pkm), for each transport mode, may not be exactly the same in the policy scenario as in the reference scenario, but we assume that the differences will be "small".

3.5 The policy entity

3.5.1 The entity that implements the policy (the sub-use cases)

Some of the monetised impacts from policy scenarios (implemented sub-use cases) can be placed under a "policy entity" (PE). This policy entity might be the public sector, e.g., city government, or some institution that administrates infrastructure or transport services. We assume that this entity will implement policy (sub-use cases), as well as collecting fees/tolls and manage the public space (for sub-use cases where this is relevant). This is a simplification; in reality, more than one institution might be involved, as well as a combination of public and private entities.

3.5.2 Cost of implementation

Proposed defaults

It is implied that the implementation costs for the policy scenarios will placed under the policy entity. We lack in most cases, however, information about how much the implementation of SUCs will cost. The costs of implementation do not include the vehicle operating and ownership costs, nor other monetised impacts; the costs of implementation comprise planning/preparation of the SUC implementation, as well as particular technical installations (hubs, etc.) that might be needed; such initial labour costs and technical installations are probable parts of the initial investment, the start-up costs. In addition, most of the implemented SUCs will probably involve some on-going monitoring, management or maintenance, which might add annual costs of implementation as long as the SUC is continuing.

In the CBA module, we include default costs of implementation (C_{impl}), both for the start-up costs (initial investment, C_{start}) and the annual management/monitoring costs (C_{monitor}). For freight and logistics SUCs, we apply cost estimates for the hubs and set all other implementation costs equal to zero. The cost figures in Table 3.6Table 2.1 are assumed to represent GDP/capita equal to 30,500 EUR_{2020}.

Table 3.6: Default costs of implementation in CBA module, EU-28 - GDP/capita in EUR_{2020} (*30,500*)

Use case	Sub-use case	Costs of implementation - default figures in CBA module	
		start-up costs (initial investment)	**monitoring, management, maintenance (annual)**
AUSS	Point-to-point AUSS connecting two modes (small-scale)	*€1,000,000*	*€10,000*
	Point-to-point AUSS in a large-scale network	*€1,000,000*	*€10,000*
	On-demand AUSS	*€1,000,000*	*€10,000*
Passenger car	Static city toll	*€1,000,000*	*€10,000*
	Dynamic city toll	*€1,000,000*	*€10,000*
	Parking behaviour	*€1,000,000*	*€10,000*
	Parking space regulation	*€1,000,000*	*€10,000*
	Dedicated lanes for AVs on urban highways	*€1,000,000*	*€10,000*
	GLOSA to connected cars	*€1,000,000*	*€10,000*
	Automated ride sharing in passenger cars	*€1,000,000*	*€10,000*

Freight and logistics	Automated urban freight delivery	*€0*	*€0*
	Automated local freight consolidation	*€8,000,000*	*€0*
	Hub-to-hub automated transfer	*€2,000,000*	*€0*

Remark: The "parking behaviour" SUC is not a regular policy measure for CBA; a parking fee exists in baseline as well as in the alternative policy cases, but we might perhaps consider the SUC as a type of monitoring measure. Regarding the start-up costs for "automated local freight consolidation" and "hub-to-hub automated transfer", the start-up costs comprise the construction of hubs, that cost €500,000 each (not including land costs); the underlying scale is a 2 million city population, which would yield, respectively, €4 million and €1 million for a 1 million city population.

The CBA/PST user will, of course, be able to change the default costs of implementation and insert the implementation costs for the selected SUC that he/she finds appropriate for his/her city case.

Probably a city government will be the policy entity that implements sub-use cases under passenger car scenarios, except perhaps for automated ride sharing which is a type of taxi service that can be implemented by some transport operator. The AUSS might also be implemented by a transport operator; while a delivery company might implement the freight and logistics sub-use cases.

Tax financing

When the policy entity is a governmental body, the costs of implementation might be financed by tax collection. It has been assessed that increased taxes leads to dead weight losses, that there is a tax financing cost. Although not obvious (Jacobs 2018) and probably depending on the policy measure, various countries have applied a so-called marginal cost of public funds that is greater than 1. E.g., the official Norwegian approach to road project (NPRA 2018) is to apply 1.2 as a default marginal cost; implying adding 20% of the cost of implementation (the start-up plus the net present value of annual monitoring costs) to the cost of implementation. However, as the LEVITATE SUCs comprise measures that might be privately financed (by transport service operators/provider), as well as being of a type that might improve economic efficiency,[107] we set the default equal to 0%.

The cost side of the benefit-cost comparison

Linking back to section 1.3, the cost of implementation is the cost side of the benefit-cost comparison. The cost of implementation (C_{impl}), carried by the policy entity, is the cost side proper of the CBA, not monetised impacts of the measure, but the particular cost of implementing the measure, the selected SUC, its planning/preparation as well as physical/technical installations.[108]

[107] Road-pricing and other LEVITATE SUCs might correct currently distorted prices, internalise external effects such that the infrastructure users take these more correctly into account, thus potentially increasing economic efficiency in society (Ballard & Fullerton 1992, Ramjerdi 1995, Brendemoen & Vennemo 1996).

[108] The benefit side comprises monetised impacts of implementing the policy, the changes in surpluses for infrastructure users (ΔIUS) and changes in monetised external effects ($\Delta M_{\text{external}}$).

3.5.3 Monetised impacts for the policy entity

Conversion of parking space in the city centre

In all SUCs, the PST-variable *parking space*, the required parking space in the city centre per person ($\bar{a}_{\text{pop\_parking\_sqm}}$) will vary. Parking space in the city centre is a scarce resource, and to the extent that changes in square metres of parking space requirement yield space for alternative use, it has economic value. The product of $\bar{a}_{\text{pop\_parking\_sqm}}$ and the *city population* (POP) yields an estimate of total required parking space in the city centre, in square metres ($A_{\text{parking\_sqm}}$).

For the SUC involving replacing on-street parking space, under passenger car SUCs, there are two of the five scenarios (sub-sub use cases) that involve conversion of parking space without specified transport-alternative use; that is: i) replacing on-street parking spaces with public spaces, and v) removing half of the on-street parking spaces.[109] In both sub-sub use cases of on-street parking space removal, we apply a 50% default, thus: $A_{\text{park\_replace\_sqm}} = \%_{\text{park\_replace}} * A_{\text{parking\_sqm}}$, assuming $A_{\text{parking\_sqm}}$ covers all parking lots in the city centre.

The average square metre value ($p_{\text{land\_sqm}}$) is applied to the required parking space change in the city centre. For the impact of altered demand for parking space, we have the following:

$$\Delta PE\_\text{inc}_{\text{parking\_space}} = p_{\text{land\_sqm}} * \left(\left(\bar{a}^{1}_{\text{pop\_parking\_sqm}} * \text{POP}\right) - \left(\bar{a}^{0}_{\text{pop\_parking\_sqm}} * \text{POP}\right)\right)$$

Similarly, for the impact of on-street parking removal, sub-sub use cases i) and v):

$$\Delta PE\_\text{inc}_{\text{parking\_removal}} = p_{\text{land\_sqm}} * \left(\left(\%^{1}_{\text{park\_replace}} * \left(\bar{a}^{0}_{\text{pop\_parking\_sqm}} * \text{POP}\right)\right) - \left(0 * \left(\bar{a}^{0}_{\text{pop\_parking\_sqm}} * \text{POP}\right)\right)\right)$$

The 0 refers to the baseline (reference) with no on-street parking space replacement implemented.

These land values will be handled as representing an income to the policy entity. If the demand for parking space increases, the increased land use to parking represents an expense that, for the PR, might be balanced by increased parking fee payments. Assumedly, this is a very simplistic approach to quantifying alterations in demand over to land-use change. However, the CBA module includes the functionality and relevant PST/CBA input can be altered by the PST/CBA user.

Fee collection from road-use and parking

Under the passenger car SUCs, we have two types of road-use pricing (static fee and dynamic fee) and a parking behaviour SUC that involves a parking fee. We have explained above, under section 2.4.4, how we derive the no. of passenger car entries to the city centre, and this number will govern the fee payments (static fee times entries, or dynamic fee times entries/7, or parking fee times duration times entries).

[109] The three other sub-sub use cases involve transport-alternative use that we do not assess directly in terms of land valuation in the CBA module; that is: ii) replacing on-street parking spaces with cycling lanes, iii) replacing on-street parking spaces with driving lanes, and iv) replacing on-street parking spaces with pick-up and/or drop-off points.

More precisely, the no. of entries by car to the city centre is total vkm by car (from PST variables) divided by average trip length ($T_{\text{car}}/\bar{T}_{\text{trip}}$). Multiplied by the static fee ($p_{\text{fee\_static}}$), it yields the collected static fee for the policy entity; the change in income between policy and baseline:

$$\Delta PE\_\text{inc}_{\text{static\_fee}} = \left(p_{\text{fee\_static}} * \left(T^1_{\text{car}}/\bar{T}_{\text{trip}}\right)\right) - \left(0 * \left(T^0_{\text{car}}/\bar{T}_{\text{trip}}\right)\right)$$

The 0 refers to the baseline (reference) with no static fee implemented.

The static fee and dynamic fee will vary, but for all levels the dynamic fee is one seventh of the static fee. The collected dynamic fee for the PE, the change between policy and baseline, is:

$$\Delta PE\_\text{inc}_{\text{dynamic\_fee}} = \left(p_{\text{fee\_dynamic}} * \left(\left(T^1_{\text{car}}/\bar{T}_{\text{trip}}\right) * \bar{T}_{\text{trip\_centre}}\right)\right) - \left(0 * \left(\left(T^0_{\text{car}}/\bar{T}_{\text{trip}}\right) * \bar{T}_{\text{trip\_centre}}\right)\right)$$

The 0 refers to the baseline (reference) with no dynamic fee implemented. Similarly, for empty km pricing:

$$\Delta PE\_\text{inc}_{\text{empty\_fee}} = \left(s_{\text{empty}} * \left(p_{\text{fee\_empty}} * \left(T^1_{\text{autcar}}/\bar{T}_{\text{trip}}\right) * \bar{T}_{\text{trip\_centre}}\right)\right) - \left(s_{\text{empty}} * \left(0 * \left(T^0_{\text{autcar}}/\bar{T}_{\text{trip}}\right) * \bar{T}_{\text{trip\_centre}}\right)\right)$$

The collected parking fee for the policy entity, the change in income between policy and baseline, is:

$$\Delta PE\_\text{inc}_{\text{parking\_fee}} = \bar{p}_{\text{fee\_parking}} * \bar{h}_{\text{hour\_parking}} * \left(T^1_{\text{car}}/\bar{T}_{\text{trip}} - T^0_{\text{car}}/\bar{T}_{\text{trip}}\right)$$

As indicated, for the parking behaviour SUC, a parking fee exists in the baseline (0) as well as in the policy implementation (1).

Summarising monetised impacts for the policy entity

One monetised impact for the PE is included in all sub-use cases, given from our monetisation of the PST-variable *parking space*: $\Delta PE\_\text{inc}_{\text{parking\_space}}$. The other monetised impacts for the PE are restricted to particular sub-use cases under passenger car scenarios; either the two versions of road-use pricing, $\Delta PE\_\text{inc}_{\text{static\_fee}}$ and $\Delta PE\_\text{inc}_{\text{dynamic\_fee}}$, and $\Delta PE\_\text{inc}_{\text{empty\_fee}}$; or two (of five) versions of the on-street parking space replacement, $\Delta PE\_\text{inc}_{\text{parking\_removal}}$. Thus:

$$\Delta PE\_\text{inc} = \Delta PE\_\text{inc}_{\text{parking\_space}} + \Delta PE\_\text{inc}_{\text{SUC}}$$

where $\Delta PE\_\text{inc}_{\text{SUC}}$ is either $\Delta PE\_\text{inc}_{\text{static\_fee}}$ or $\Delta PE\_\text{inc}_{\text{dynamic\_fee}}$ or $\Delta PE\_\text{inc}_{\text{empty\_fee}}$ or $\Delta PE\_\text{inc}_{\text{parking\_fee}}$ or $\Delta PE\_\text{inc}_{\text{parking\_removal}}$ or zero.

Summarising fee collections and implementation costs for the policy entity

The net result for the policy entity will be the change in fee collection (income), between baseline (0) and policy (1), ΔPE_inc, minus the costs of implementation, C_{impl}:

$$\Delta PE = \Delta PE\_\text{inc} - C_{\text{impl}}$$

In the AUSS and freight transport cases, the PE might also be the owner of the vehicles, the PE being the transport service provider. The generalised framework of the CBA module disentangles the particular domain of the policy entity from the transport service providers. In any case, an aggregation of ΔPS for AUSS or for freight transport providers and $\left(\Delta PE\_\text{inc} - C_{\text{impl}}\right)$ will be easily accessible from the CBA results.

3.6 Summary of output from the CBA module

3.6.1 Main impact categories

Table 3.7 summarises the categories that comprise the output from the CBA module.

Table 3.7: Overview of main categories, sub-categories, and agents

Main impact categories	Sub-categories of impacts	Agents (modes) of impacts
Monetised impacts for infrastructure users ($\Delta CS + \Delta PS$)	Consumer surplus changes for transport consumers	Passenger car (manual & automated) Active transport (cycle & walk) Public transport (rail & bus) Automated shuttle bus (& automated ride-sharing cars)
	Producer surplus changes for transport service providers	Public transport (rail & bus) Automated shuttle bus (& automated ride-sharing car) Freight transport (manual & automated)
Monetised external effects (ΔM)	Attributed monetised external effects (emissions, crashes, congestion) to transport modes	Passenger car (manual & automated) Public transport (rail & bus) Automated shuttle bus (& automated ride-sharing cars) Freight transport (manual & automated)
Policy entity (ΔPE)	Sub-use case specific income Cost of implementation	Policy entity (public or private)

The CBA module includes logic and dependencies that ensure that the selected SUC's relevant elements are included within the various impact and cost functions. Hence, the "total effect" formulas consist of multiple different functions for the various agents.

3.6.2 Additional functionalities of the CBA module

The final CBA results

Net present value (NPV)

All the above-mentioned monetised impacts (Table 3.7), the changes from reference (baseline) to policy implementation, are summarised into a net present value (NPV). The NPV can be described as showing today's (or a certain year's) value of the present and future cash flow and takes into account the investment's alternative use. NPV can also be described as the discounted value of all changes in monetised impacts over the project period minus the discounted value of the costs of implementation. The latter may also be brought forward to benefit-cost ratio, which might be useful in comparing SUCs of different scopes and sizes.[110]

[110] If the NPV equals: $\text{present value of monetised impacts ("benefits")} - \text{present value of costs of implementation}$, then the benefit-cost ratio equals: $\frac{\text{present value of benefits}}{\text{present value of costs of implementation}}$. If the decision-maker wants to put more weight on budget limitations, the net-benefit-cost ratio equals: $\frac{\text{NPV}}{\text{present value of costs of implementation}}$.

Break-even analysis
Figure 3.2 illustrates a break-even analysis.

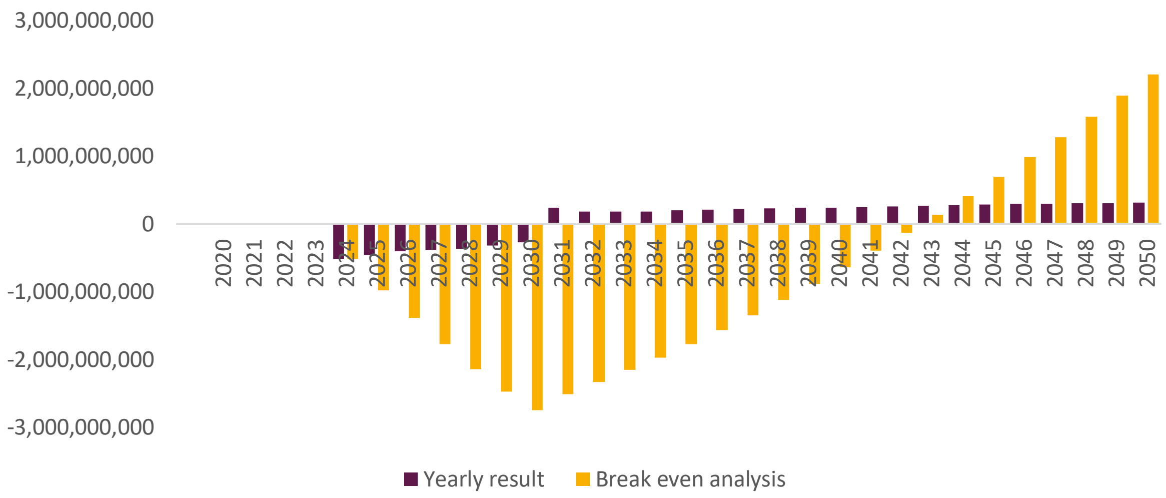


Figure 3.2: Break-even analysis

The break-even analysis shows all the annual results ("cash flow", shown in purple bars) and the accumulated sum of all the annual results (at the start of the year, shown in orange bars). If there is an investment cost that will yield positive benefits over time, the development will resemble that in Figure 3.2; the cumulative sum of the annual results will show the break-even when/if the sub-use case turns out positive. In the figure, the first years have a negative net economic value, such that negative values accumulate over the first years. Then, the annual results turn positive and the accumulated "loss" is reduced; the total monetised effect of the policy is turning to positive from 2042 to 2043, so the year 2043 is then called the break-even year.

CBA-specific project lifetime and residual value
The PST has a fixed period of analysis in its database, ranging from 2020 to 2050. To adjust this to the PST/CBA users' evaluation of the sub-use cases, the user chooses the project implementation year. If the user chooses implementation year 2025, the PST period of analysis will then be from 2025 to 2050.

The CBA module enables an additional user specification of the project lifetime, such that the assessed impact from policy can be shorter than until 2050, but also longer. E.g., if the user set a lifetime of 20 years, and implementation year is 2025, the project lifetime is subsequently from 2025 to 2045. The CBA module will then adapt the calculation of impacts until 2045 instead of 2050.

Conversely, if the user set the project lifetime to 30 years, and implementation year is 2025, the project lifetime lasts until 2055, which is beyond the PST 2050 limit. In practical terms, omitting the years from 2050 to 2055 might yield an under- or overestimation of monetised impacts. The CBA module caters for such potential effects by calculation of the project's residual value. In that case we assume that the yearly flow of net benefits (net monetised impacts) in the residual value period falls linearly towards zero in the last year of the project lifetime (falling linearly from 2050 to zero in 2055). If the cash slow in the last PST year (2050) is negative, i.e., the net benefit in 2050 is zero, the residual value analysis is not conducted. Maximum residual value end year is 2099.

CBA sensitivity analysis

Due to the apparent uncertainties in predicting and simulating the future, we conduct sensitivity analyses of central impacts that are calculated in LEVITATE. It will be illustrated how the result (NPV) changes if the value of a chosen variable is 50% higher or lower than the default of the policy scenario. The variables tested in sensitivity analysis will comprise:

- the amount of travel,
- the delay,
- the parking space, and
- the CO_2 emission.

In addition, the sensitivity anlysis will also comprise the costs of implementation. We lack information about the order of magnitude of these costs, except the hub cost estimates for freight transport consolidation and hub-to-hub. Although the PST/CBA user can insert such cost figures, we will propose a higher interval of variation for this figure, possibly ±1000%, i.e., 10 times higher or lower.

4 CBA module operation – preliminary analyses

The present chapter shows examples of how the CBA module will operate, within its spreadsheet model structure; it has been created in Microsoft Excel 2016. The same structure and facilities are assumed to be programmed into the online PST as an add-on CBA module. This chapter will also provide results for a hypothetical case area. We stress their hypothetical status. Moreover, for most of the Levitate policies, the passenger car and automated urban shuttle service use cases, we lack estimates of the costs of implementation. We use the default starting values in the PST, which could be correct in some cities and not in other cities. Uncertainties and lack of precision are of course inherent to any predictions, but the preliminary CBA analyses may still provide some guidance.

4.1 PST input and specific CBA input

4.1.1 PST input applied in the CBA

The PST user will firstly select between the forecasting or backcasting approach to policy assessment (or have a look into the knowledge module). A CBA is primarily cast as a forecasting methodology; hence, we describe the CBA module within the framework of the PST forecasting part.[111] Selecting forecasting, the PST user will face the selection of policy; the use case (passenger car, AUSS, or freight) and its sub-use case, as well as specifying the CCAM deployment scenario (pessimistic, neutral, or optimistic). Under the policy choice the PST user can adjust some PST initial (baseline) defaults. The primary PST initial parameters applied into the CBA module are listed in Table 4.1.

Table 4.1 PST input parameters, area-specific initial baseline values (before policy implementation)

Parameter	**Unit of measurement**	**Default initial value** (can be changed by user)
GDP per capita	€	17,000
Annual GDP per capita change	%	1.5%
Inflation	%	1.0%
City population	million persons	0,5
Annual city population change	%	0.5%

Source: Ziakopoulos et al. (2022, Table 3.1).

[111] Obviously, the CBA can also be applied to the PST "solution(s)" for a backcasting policy selection, where the policy is induced in the PST from a user selection of parameter targets (Ziakopoulos et al., 2022).

There are other PST area-specific baseline parameters that have an impact on the CBA. The PST user can alter the baseline default of 100% manual (human-driven) vehicles, setting both automated 1st gen. cars (cautious) and the automated 2nd gen. cars (aggressive) higher than 0%. There are also underlying impacts on the PST result from other initial baseline values, that the PST user can change; the fuel cost and the fuel consumption, the electricity cost and the electricity consumption, and the crash-related parameters "VRU reference speed" and "VRU at-fault accident share". These parameters are not applied directly in the CBA module. That also applies to the two last PST initial parameters, the "average load per freight vehicle" and "average annual freight transport demand".[112]

Table 4.2 PST impact parameters, initial default baseline values (before policy implementation)

Impact	Description / measurement	Default initial value	SUC where impact is omitted from PST
Direct impacts			
Travel time	*Average duration (min) of a 5 km trip inside the city centre*	*15*	
Vehicle operating cost	*Direct outlays (€/vkm) for operating a vehicle per km of travel*	*0.25*	*Not in freight tr. UCs*
Systemic impacts			
Amount of travel	*Person km of travel per year in the area*		*Not in freight tr. UCs*
Congestion	*Average delays to traffic (sec./vkm) as a result of high traffic volume*	*197.37*	*Not in city toll SUC*
Modal split, public transport	*% of trip distance made using public transportation*	*40%*	*Not in freight tr. UCs*
Modal split, active travel	*% of trip distance made using active transportation (walking, cycling)*	*3%*	*Not in freight tr. UCs*
Vehicle occupancy	*average % of seats in use (5 seats car)*	*25%*	*Not in freight tr. UCs*
Wider impacts			
Parking space	*Required parking space (m^2) in the city centre per person*	*0.9*	
NO_X due to vehicles	*Concentration of NO_X, g/vkm*	*1.80*	*Not in city toll SUC*
PM_{10} due to vehicles	*Concentration of PM_{10}, g/vkm*	*0.20*	*Not in city toll SUC*
CO_2 due to vehicles	*Concentration of CO_2, g/vkm*	*2500*	*Not in city toll SUC*
Commuting distances	*Average sum length of trips to and from work*	*20*	*Not in freight tr. UCs, nor in AUSS point-to-point SUC*
Road safety total effect	Weighted sum of crashes (per mill. vkm) between motorised vehicles and (injury) crashes between motorised and VRU		*Not in freight tr. UCs, nor in city toll SUC*

Source: Ziakopoulos et al. (2022, Tables 3.2 & 3.5).

[112] Some of these parameters were considered applied in the CBA module. E.g., the annual freight demand (in million tonnes) divided by the average load per freight vehicle (in tonnes) would yield an estimate of annual freight trips in the policy area. The average load also provides a possible link between the freight transport cost and the vehicle operating and ownership costs. But we lack in any case the information about the freight vehicle combination (the shares of LCV and HGV) and the average trip distances; and the freight transport cost (per tonne km) is only available under the freight transport scenarios, while the freight SUCs are based on different freight vehicle input. The fuel and electricity consumptions and costs have been applied into the default voc for freight vehicles, and we have also shown applications to other vehicles, but we lack the other input (acquisition costs, maintenance, insurance, etc.) for deriving voc from these parameters.

A set of values of initial baseline impacts, that the PST user can adjust, are listed in Table 4.2 (Ziakopoulos et al., 2022). The baseline is in principal the same for all SUCs that are to be applied within an area.

The initial values in Table 4.2 are being used in the CBA examples in this chapter. Some of the values are likely to be on the high end of the spectrum, and thus, the initial values presented in Table 4.2 can be correct in some areas and not correct at all in other areas. Due to the initial value affecting the result of the CBA, it is important that when users of the online tool are doing their analysis, they should strive to have as precise initial values as possible.

As indicated, for some use cases and SUCs, various impacts are not provided in the PST. We have indicated how these omissions are handled within the CBA module (see section 2.4.4). In general, if variables listed in Table 4.2 are omitted, they will be invoked by use of defaults or derived from functions using other PST variables. Then these variables should remain equal in policy as in reference (baseline); but they might still yield minor indirect impacts if correlated with PST variables that differ between policy and reference.

Importantly, the PST user also selects the policy implementation year.

4.1.2 Additional CBA-specific input

Table 4.3 lists additional input-variables that are applied in the CBA module; default initial values that the PST/CBA user can change/correct.

Table 4.3 CBA-specific input parameters, area-specific initial baseline values (before policy implementation)

Parameters	**Unit of measurement**	**Default initial value** (can be changed by user)
Principal variables for user input/correction		
Policy implementation cost	€	Various, but no real defaults for passenger transport measures
Discount rate	*%*	3%
Project lifetime	*Years*	2050 minus selected "implementation year" (PST)
Secondary variables for user input/correction		
Shares of pkm and vkm, various transport modes	*%*	Various
Occupancies	*Numeric*	Various
Tertiary variables for user input/correction		
Population affected by policy measure	*Numeric*	"city population" (PST)
Value of undeveloped land in the selected policy area	*€/m²*	€300
Vehicle operating and ownership costs, various modes	*Numeric*	Multipliers of "vehicle operating cost" (PST)
Ticket price, public transport single-trip	*€/trip*	€2.70
Value of travel time savings (VTTS)	*Numeric*	Multipliers of VTTS/h for travel by car (in free flow)
Social congestion costs	*€/vkm*	Various
Emission costs (NO_x, PM_{10}, CO_2)	*€/kg*	Various
Weighted average cost of a crash	*€/crash*	€14,800 €
Income elasticity	*Numeric*	0.5
Tax financing cost (on the cost of implementation)	*%*	0%

The Euro values listed in

Table 4.3 represent EUR_{2020} for an underlying GDP/capita of approximately €30,500. We have differentiated between principal variables, where user input/correction is most decisive, secondary inputs that describe the transport (elements that are not already registered in the PST), and tertiary variables that the user should have the possibility to alter but probably to a lesser extent able to providing decisive corrections.[113] PST/CBA user input/corrections will "overwrite" table content that enters the CBA module, various content of tables presented in sub-chapters 2.2 and 2.4.

Applying the input form the PST and the additional CBA input, the CBA module can carry out the estimations of monetised changes from selection of single policies (SUCs) or combinations of two different SUCs. That will yield the estimated consumer surplus changes, producer surplus changes, external cost changes, and the monetised change for the policy entity that implements the SUC. Preliminary analyses are shown in the following sub-chapter.

4.2 Use of the CBA module – examples

4.2.1 Use case: automated urban shuttle service (AUSS)

SUC: Point-to-point AUSS connecting two modes (Shuttle bus service), Peak hour – Dedicated lane, inputs

For all AUSS SUCs we apply the same default cost of implementation; €1 million as start-up cost and €10,000 as average annual running costs. These cost levels represent EU-28 average values, EUR_{2020} for an underlying GDP/capita of approximately €30,500. This equals €557,377 as start-up cost and €5,574 as average annual running costs with GDP/capita of €17,000. The 1 million start-up costs and 10,000 running costs are set arbitrarily.

Total annual amount of person travel in the case area is set arbitrarily to 2 billion pkm. As shown in Table 2.26, the smaller point-to-point SUC connecting two modes would represent 0.07% of total pkm; thus 1.4 million pkm annually. As the average occupancy is assumed to be 5, the annual vkm of the shuttle fleet is 280,000. Multiplying daily pkm by all passenger transport modes in Table 2.26, 1,820,602, by 250, it yields an annual pkm estimate of 455,150,578.[114] Thus, if the shuttle fleet no. is 4 in that case, it will be 17.6 (or 18) if pkm is 2 billion. If we assume that the average annual (workday) travel length per person is 4000 km, the derived population in the case area is 500,000.

We apply a default modal split of total pkm into 40% public transport, 3% active transport (50-50 cycle-walk), and subsequently 57% car transport. A default vkm-weighted occupancy of 28 in the various public transport modes (beyond AUSS), yields approximately 2.85%, 6%, and 91.15% vkm distribution of these three modes. If total vkm by public transport is 800,000/28=28,571,429, we have that 280,000 is vkm of the

[113] The division of the user input/correction option in two hierarchically structured sections might also facilitate the input/correction task for the PST/CBA user.

[114] Applying 250 instead of 365 when aggregating from operating days to annual operation will indicate that the analysis is based on workdays of the year, omitting weekends and holidays that will have different transport patterns.

automated shuttles and 28,291,429 is the vkm by other public transport.[115] If 1.4 million pkm is carried out by automated shuttles, the remaining pkm by other public transport is 798.6 million.

All initial baseline values are for the year 2020; the values over the period are discounted back to 2020 as well. The population and, subsequently, the amount of travel and other PST variables, will grow until 2025. From 2025 and onwards some variables will develop differently between reference (baseline) and policy.

SUC: Point-to-point AUSS connecting two modes (Shuttle bus service), Peak hour – Dedicated lane, results

Overview of main input and main results

The PST/CBA user will face the following first overview of the CBA and main results:

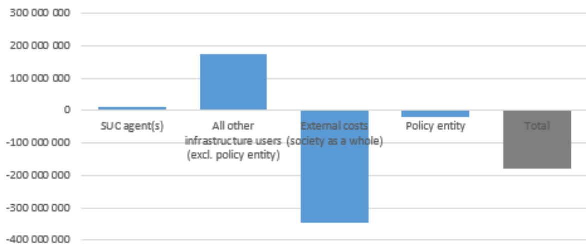
Main results			
Result (nominal)	-	136 854 985	2025-euros
Result as net present value (NPV)	-	179 115 406	2020-euros
Result per invested euro in NPV	-	143,29	This means that per euro you spend on this sub-use case, you have a net loss of 143,3 euros in NPV.
Result per year as an annuity in NPV	-	6 889 054	
Result per vkm in NPV	-	0,01	

Regarding the main CBA results, in addition to the NPV, the overall discounted result of the policy measure, also nominal results for the period are shown, as well as a net benefit-cost ratio.

In this specification of the SUC, we see that the SUC has a net negative effect and that it is quite strong when we compare the effect with the cost of the measure (*Result per invested euro in NPV*).

Moreover, there is a simple distributional result table that singles out the net impact for the main SUC agent(s), in this case, the AUSS (providers and consumers), which the policy is directed towards, and other main agents (other infrastructure users, external effects and policy entity (the organization implementing the policy)):

Graphical illustration of main agents		Result for the whole period of analysis
SUC agent(s)		11 931 782
All other infrastructure users (excl. policy		176 185 628
External costs (society as a whole)	-	345 888 877
Policy entity	-	21 343 939
Total	-	179 115 406



The distributional result showcases that while the total effect is negative, there are some positive effects, e.g. a combined positive effect for the infrastructure users (passenger

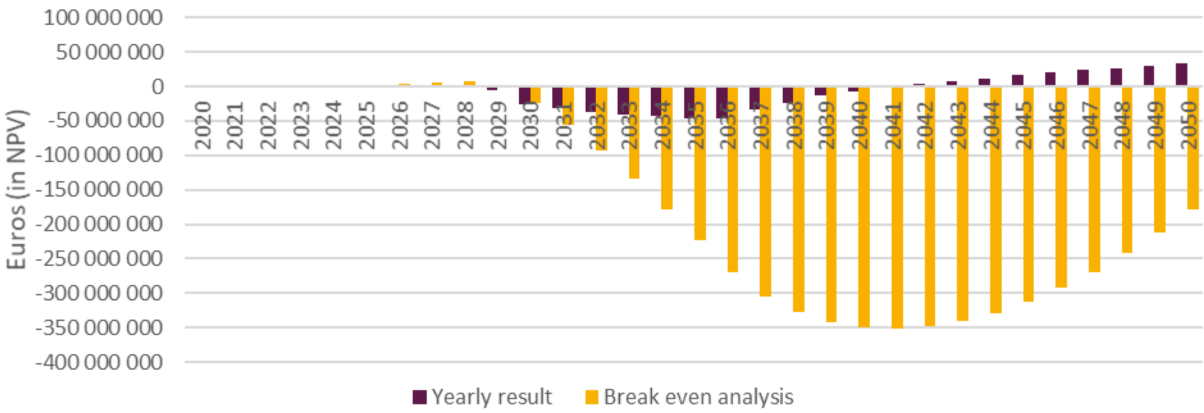
[115] For the given occupancies, respectively 28, 1, and 1.25, total passenger vehicle vkm is 1,000,571,429; and we can then derive a 1/9 freight transport vkm equal to 111,174,603 (100,057,143 vkm by LCV and 11,117,460 vkm by HGV), which is applied for the emission cost allocation (see section 2.2.3).

cars, public transport, freight providers, etc.). The positive effect for the infrastructure users is, however, overshadowed by the large negative change in external costs.

The user can then examine additional analyses and more detailed result tables, as presented in the following.

<u>Break-even analysis and residual value</u>

The break-even analysis for the SUC of the AUSS is presented below, and the analysis shows when or if the total investment cost yields a positive return:



In the figure, purple bars represent the SUCs yearly effect, while the orange bars represent the accumulated yearly effects. The figure shows that while there seems to be a positive trend in the later years of the period of analysis, the SUC has a negative effect, as shown earlier.

A project lifetime of 25 years, when implementation year is 2025, implies project end year in 2050 (2025+25) and hence a residual value is not calculated.

<u>Distributional result summary</u>

The CBA module carries out estimations via transport modes, split into transport consumers and transport service providers. Hence, a distributional summary is enabled, showing the changes in consumer surpluses and producer surpluses. The change in external effects and the change (in net income) for the policy entity are included as well. The distributional CBA results are shown as €/year (in NPV) and €/year/vkm (in NPV) for the agents and for the main groups of impact variables.

Table 4.4 CBA output per agent – hypothetical case area – shuttle bus service, peak hour dedicated lane

Agent	Monetised impacts, €/year (in NPV)	Monetised impacts, € (in NPV)/vkm
Active transport users	59,453	0.001
Passenger cars, autonomous - user	5,970,007	0.027
Passenger cars, manual - user	-9,973,974	-0.022
Public transport - user	-	-

Public transport - provider	6,612,082	0.294
AUSS + ride-sharing users	-	-
AUSS + ride-sharing providers	458,915	2.097
SUC freight providers	-	-
Non-SUC freight providers	4,108,804	0.046
External costs	-13,303,418	-0.016
Policy entity	-820,921	-0.001
Overall result, NPV, EUR2020/year	-6,889,054	-0.008

The distributional result showed that while the total effect is negative, there are some positive effects, e.g. a combined positive effect for the infrastructure users. The largest effect is the change in external costs, which is, relative to the other effects, quite strong and negative. The users of manual cars are also adversely impacted by the SUC, while other infrastructure users are positively impacted (Table 4.4).

Regarding the distribution of NPV over impacts, Table 4.5 shows that the main contributors to the negative overall result are the travel time / delay and CO_2 emissions, while "vehicle operating and ownership" and "parking space" are the main positive impacts.

Table 4.5 CBA output per impact – hypothetical case area – shuttle bus service, peak hour dedicated lane

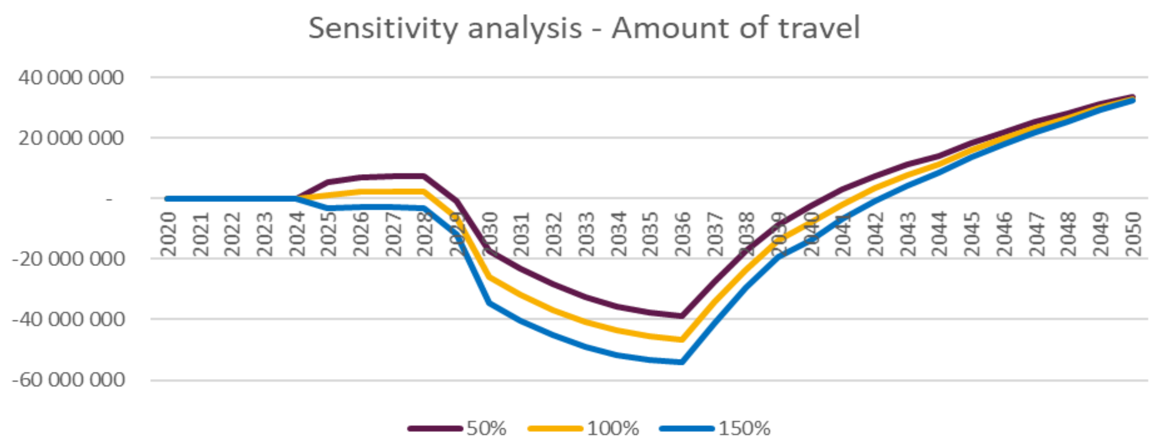
Impact	**Monetised impacts, €/year (in NPV)**	**Monetised impacts, € (in NPV)/vkm**
Travel time & internal delay impact	-10,779,733	-0.013
Vehicle operating & ownership	9,817,098	0.012
Parking space (& fares, fees)	6,810,186	0.008
Internal crash risk impact	610,657	0.001
External crash risk impact	593,475	0.001
External delay impact	-2,070,230	-0.002
Emissions, NO_X & PM_{10}	-1,770,636	-0.002
Emissions, CO_2	-10,056,027	-0.012
Policy implementation	-43,844	-0.000
Overall result, NPV, EUR2020/year	-6,889,054	-0.008

<u>Sensitivity analysis</u>
The CBA module conducts sensitivity analyses for the implementation cost, as well as the growth rate of amount of travel, delays, parking space and CO_2 emissions.

The sensitivity analysis shows the estimated net benefits under varying assumptions for selected variables in the calculations, a lower and a higher alternative to the default estimate (±50%). In this example, we show how NPV for the project will be influenced by ±50% change in the annual growth rate of the amount of travel; neither a lower nor a higher change will tip the NPV towards a positive figure:

	Total NPV
50%	-48,850,655
100%	-179,115,406
150%	-309,088,922

The illustration below shows the NPV development over time, including the sensitivity analysis interval:



4.2.2 Use case: passenger cars

SUC: road-use pricing (city toll), static toll, €5 per city centre entry - input
For all passenger car SUCs we also apply the same arbitrary default cost of implementation; €1 million as start-up cost and €10,000 as average annual running costs. These cost levels represent EU-28 average values, EUR$_{2020}$ for an underlying GDP/capita of approximately €30,500. That cost level also applies to the €5 static fee per passenger car entry into the city centre. This implementation cost equals €557,377 as start-up cost and €5,574 as average annual running costs GDP/capita of €17,000.

Total annual amount of person travel in the case area is set arbitrarily to 2 billion pkm. The population in the case area is set to 500,000. We apply a default modal split of total pkm into 40% public transport, 3% active transport (50-50 cycle-walk), and subsequently 57% car transport. A default vkm-weighted occupancy of 28 in the various public transport modes yields approximately 2.85%, 6%, and 91.15% vkm distribution of these three modes.[116] The share of automated passenger cars is given by the selected CCAM deployment scenario and the underlying MPR.

[116] As in the example above, for the given occupancies, respectively 28, 1, and 1.25, total passenger vehicle vkm is 1,000,571,429; and we can then derive a 1/9 freight transport vkm equal to 111,174,603 (100,057,143 vkm by LCV and 11,117,460 vkm by HGV), which is applied for the emission cost allocation (see section 2.2.3). The share of automated freight vehicles is also given by the selected CCAM deployment scenario and the underlying MPR.

As indicated under section 2.4.4, we assume that under road-use pricing SUCs all travel by car either involves destinations in the city centre or destinations beyond whereby passing through the centre. Then the vkm by car, $T_{\text{car}} = Q_{\text{car}}/n_{\text{occ\_car}}$, can be divided by average trip length ($\bar{T}_{\text{trip}}$) to produce an estimate of the no. of entries by car to the city centre. For each passenger car entry there is a €5 payment (to the policy entity).

All initial baseline values are for the year 2020; the values over the period are also discounted back to 2020. The population and, subsequently, the amount of travel and other PST variables, will grow until 2025. From 2025 and onwards some variables will develop differently between reference (baseline) and policy.

SUC: road-use pricing (city toll), static toll, €5 per city centre entry – results

<u>Overview of main input and main results</u>
The PST/CBA user will face the following first overview of the CBA and main results:

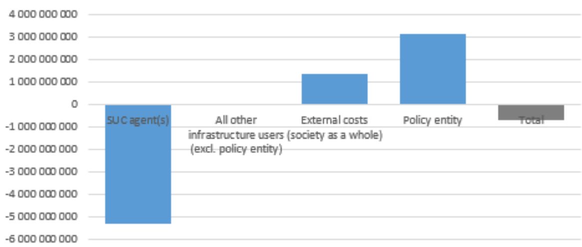
Main results			
Result (nominal)	-	993 926 759	2025-euros
Result as net present value (NPV)	-	691 087 939	2020-euros
Result per invested euro in NPV	-	552,87	This means that per euro you spend on this sub-use case, you have a net loss of 552,9 euros in NPV.
Result per year as an annuity in NPV	-	26 580 305	
Result per vkm in NPV	-	0,04	

Regarding the main CBA results, in addition to the NPV, the overall discounted result of the policy measure, also nominal results for the period are shown, as well as a net benefit-cost ratio.

In this specification of the SUC, we see that the SUC has a net negative effect and quite strong negative effect when we compare the effect with the cost of the measure (*Result per invested euro in NPV*).

Moreover, there is a simple distributional result table that singles out the net impact for the main SUC agent(s), in this case, the passenger cars (autonomous and manual), which the policy is directed towards, and other main agents (other infrastructure users, external effects and policy entity (the organization implementing the policy)):

Graphical illustration of main agents		Result for the whole period of analysis
SUC agent(s)	-	5 278 490 937
All other infrastructure users (excl. policy		45 540 560
External costs (society as a whole)		1 378 150 424
Policy entity		3 163 712 014
Total	-	691 087 939

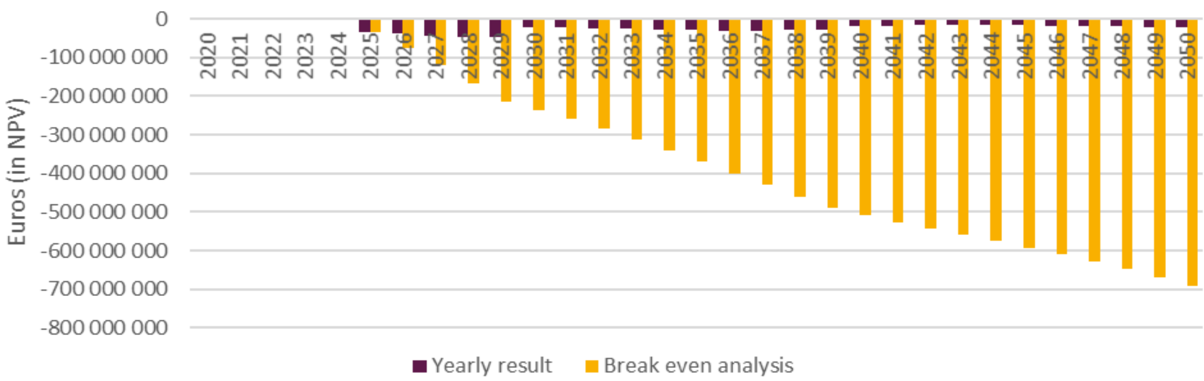


The distributional result showcases that while the total effect is negative, there are some positive effects, e.g. a combined positive effect for the external costs (CO2 emissions, crashes, delays, etc.).

The user can then examine additional analyses and more detailed result tables, as presented in the following.

Break-even analysis

The break-even analysis for the SUC of the AUSS is presented below, and the analysis shows when or if the total investment cost yields a positive return:



In the figure, purple bars represent the SUCs yearly effect, while the orange bars represent the accumulated yearly effects. The figure shows that the SUC has a negative effect, as shown earlier, and that it seems to follow that negative trend the whole period of analysis.

A project lifetime of 25 years, when implementation year is 2025, implies project end year in 2050 (2025+25) and hence a residual value is not calculated.

Distributional result summary

The CBA module carries out estimations via transport modes, split into transport consumers and transport service providers. Hence, a distributional summary is enabled, showing the changes in consumer surpluses and producer surpluses. The change in external effects and the change (in net income) for the policy entity are included as well. The distributional CBA results are shown as €/year (in NPV) and €/year/vkm (in NPV) for the agents and for the main groups of impact variables.

Table 4.6 CBA output per agent – hypothetical case area – static toll, €5

Agent	**Monetised impacts, €/year (in NPV)**	**Monetised impacts, € (in NPV)/vkm**
Active transport users	-188,567	-0.003
Passenger cars, autonomous - user	-61,071,073	-0.435
Passenger cars, manual - user	-141,947,809	-0.474
Public transport - user	180,723	0.007
Public transport - provider	14,153,619	0.530
AUSS + ride-sharing users	-	-
AUSS + ride-sharing providers	-	-
SUC freight providers	-	-

Non-SUC freight providers	-12,394,216	-0.162
External costs	53,005,786	0.088
Policy entity	121,681,231	0.201
Overall result, NPV, EUR2020/year	-26,580,305	-0.044

Table 4.6 shows that the largest effect is the effect on passenger car users (both manual and autonomous), which is, relative to the other effects, quite strong and negative. Public transport, external effects, and the policy entity, on the other hand, gain in terms of NPV.

Table 4.7 shows that the main contributors to the negative overall NPV result are the travel time / delay changes and "vehicle operating & ownership" (increased voc), while CO_2 emissions and external congestion cost are the main positive impacts.

Table 4.7 CBA output per impact – hypothetical case area – static toll, €5

Impact	Monetised impacts, €/year (in NPV)	Monetised impacts, € (in NPV)/vkm
Travel time & internal delay impact	-45,603,188	-0.075
Vehicle operating & ownership	-33,961,735	-0.056
Parking space (& fares, fees)	-781,740	-0.001
Internal crash risk impact	804,415	0.001
External crash risk impact	675,804	0.001
External delay impact	16,660,388	0.028
Emissions, NO_X & PM_{10}	4,824,972	0.008
Emissions, CO_2	30,844,621	0.051
Policy implementation	-43,844	-0.000
Overall result, NPV, EUR2020/year	-26,580,305	-0.044

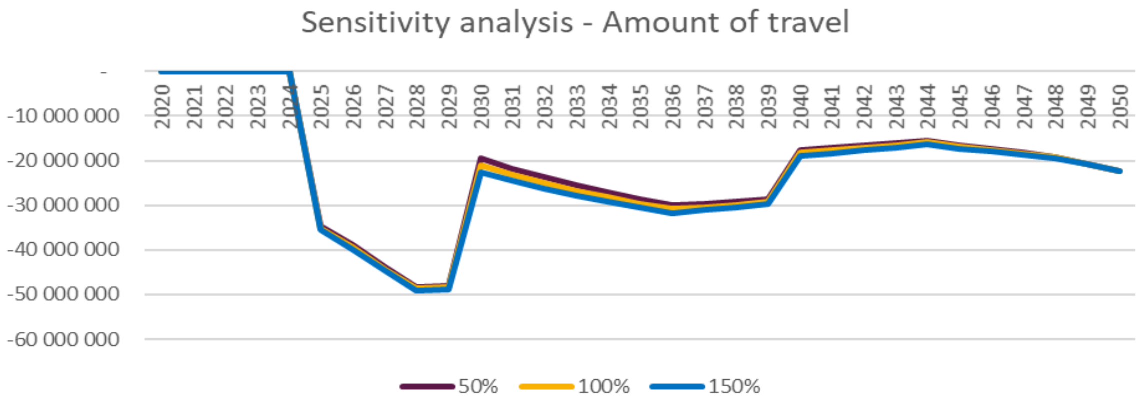
Sensitivity analysis

The CBA module conducts sensitivity analyses for the implementation cost, as well as the growth rate of amount of travel, delays, parking space and CO_2 emissions.

In this example, we show an example of the results for ±50% of the annual growth rate of amount of travel; the NPV result barely changes:

	Total NPV
50%	-675,116,341
100%	-691,087,939
150%	-707,034,221

The illustration below shows how the sensitivity analysis interval fluctuates over the project period:



4.2.3 Use case: freight transport and logistics

SUC: Automated consolidation delivery - inputs

For freight transport SUCs we do have specific proposals for start-up costs, the costs of hubs in the case of consolidation and hub-to-hub (Table 3.6). For consolidation it is assumed a need for 8 hubs per million inhabitants; thus for 500,000 inhabitants in the case area, 4 hubs will be installed under the policy scenario (while manual delivery with no consolidation and no hubs is the reference). The cost per hub is set to €500,000 (Table 3.6); this cost level represents EU-28 average values, EUR_{2020} for an underlying GDP/capita of approximately €30,500. This cost per hub equals €278,689 for an underlying GDP/capita of €17,000.

The scaling with respect to population also affects freight SUC vkm. If the baseline level for a population of 2 million inhabitants is 80,389 daily (Table 2.31), it will be a fourth when the population is 500,000; thus 20,097. While the vkm of automated consolidation is 42,792 (32,347 LCV + 10,445 HGV) in the case of 2 million inhabitants (Table 2.3), it will be 10,698 (8087 LCV + 2611 HGV) per day in the case of 500,000 inhabitants. The annual vkm for the SUC fleet of freight vehicles are 6,270,359 in the reference (manual delivery, all by manual LCV) and 3,337,756 with policy implementation (automated consolidation, 2,523,046 by automated LCV and 814,710 by automated HGV).[117]

The non-SUC freight is calculated as 6,270,359×4 (as the SUC freight is assumed to represent 20% of all freight in the area), split into 90% vkm by LCV and 10% vkm by HGV; and the shares of automated vs. manual freight vehicles is given by the selected CCAM deployment scenario and the underlying MPR for freight vehicles. (Passenger transport is calculated as 9 times the sum of SUC-freight and non-SUC freight).

All initial baseline values are for the year 2020; the values over the period are also discounted back to 2020. The population and other variables will grow until 2025. From 2025 and onwards some variables will develop differently between reference (baseline) and policy.

[117] For freight transport 312 is applied as annual operating days.

SUC: automated consolidation – results

Overview of main input and main results

The PST/CBA user will face the following first overview of the CBA and main results:

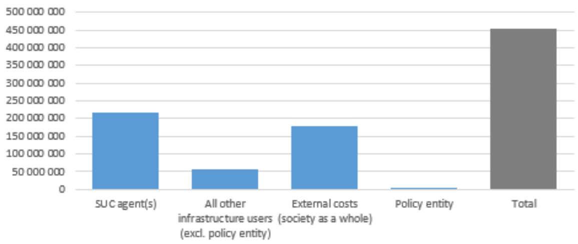
Main results		
Result (nominal)	619 676 727	2025-euros
Result as net present value (NPV)	453 356 908	2020-euros
Result per invested euro in NPV	226,68	This means that per euro you spend on this sub-use case, you have a net benefit of 226,7 euros in NPV.
Result per year as an annuity in NPV	17 436 804	
Result per vkm in NPV	0,23	

Regarding the main CBA results, in addition to the NPV, the overall discounted result of the policy measure, also nominal results for the period are shown, as well as a net benefit-cost ratio.

In this specification of the SUC, we see that the SUC has a net positive effect and also quite strong positive effect when we compare the effect with the cost of the measure (*Result per invested euro in NPV*).

Moreover, there is a simple distributional result table that singles out the net impact for the main SUC agent(s), in this case, the freight transport provider (in the SUC, not the non-SUC freight), which the policy is directed towards, and other main agents (other infrastructure users, external effects and policy entity (the organization implementing the policy)):

Graphical illustration of main agents	Result for the whole period of analysis
SUC agent(s)	216 462 049
All other infrastructure users (excl. policy	56 530 901
External costs (society as a whole)	180 247 226
Policy entity	116 732
Total	453 356 908

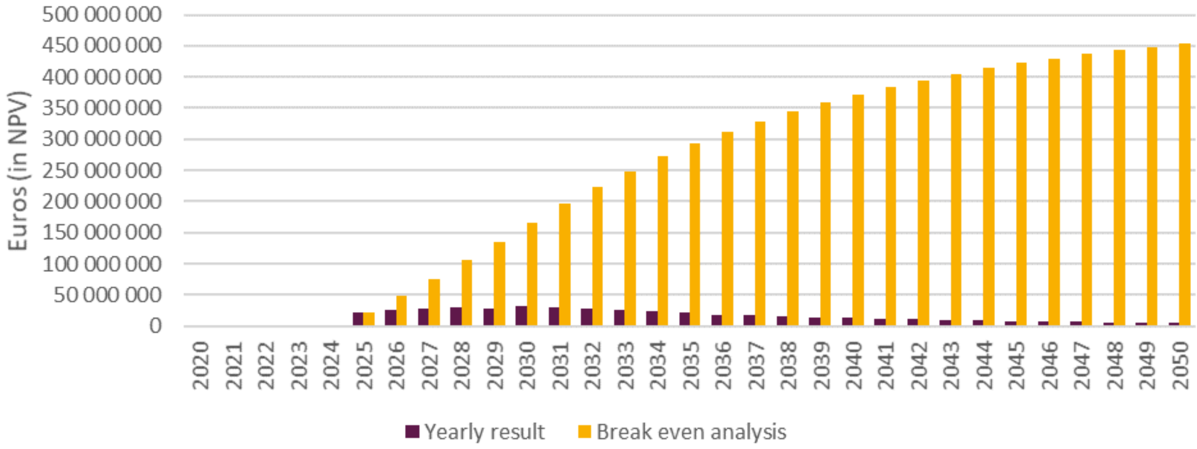


The distributional result showcases that the total effect is positive, and at the same time positive for the main agents.

Following these results, the user can examine additional analyses and more detailed result tables, as presented in the following.

Break-even analysis

The break-even analysis for the SUC of the automated freight consolidation is presented below.



In the figure, purple bars represent the SUCs yearly effect, while the orange bars represent the accumulated yearly effects. The figure shows that the SUC has a positive effect, and that the yearly results all are positive, so the accumulated result is increasing each year.

A project lifetime of 25 years, when implementation year is 2025, implies project end year in 2050 (2025+25) and hence a residual value is not calculated.

<u>Distributional result summary</u>

The CBA module carries out estimations via transport modes, split into transport consumers and transport service providers. Hence, a distributional summary is enabled, showing the changes in consumer surpluses and producer surpluses. The change in external effects and the change (in net income) for the policy entity are included as well. The distributional CBA results are shown as €/year (in NPV) and €/year/vkm (in NPV) for the agents and for the main groups of impact variables.

Table 4.8 CBA output per agent – automated consolidation

Agent	Monetised impacts, €/year (in NPV)	Monetised impacts, € (in NPV)/vkm
Active transport users	9,523	0.003
Passenger cars, autonomous - user	-267,536	-0.019
Passenger cars, manual - user	1,273,355	0.045
Public transport - user	-	-
Public transport - provider	-	-
AUSS + ride-sharing users	-	-
AUSS + ride-sharing providers	-	-
SUC freight providers	8,325,463	3.350
Non-SUC freight providers	1,158,924	0.042
External costs	6,932,586	0.091
Policy entity	4,490	0.000
Overall result, NPV, EUR2020/year	17,436,804	0.228

Table 4.8 above shows that the largest effect is the effect on freight, especially SUC freight providers, but also the change in external costs are significant.

Table 4.9 under shows that the main contributors to the positive overall result are the travel time / delay, voc, and CO_2 emissions.

Table 4.9 CBA output per impact – automated consolidation

Impact	Monetised impacts, €/year (in NPV)	Monetised impacts, € (in NPV)/vkm
Travel time & internal delay impact	3,492,525	0.046
Vehicle operating & ownership	6,961,920	0.091
Parking space (& fares, fees)	79,172	0.001
Internal crash risk impact	45,285	0.001
External crash risk impact	523,787	0.007
External delay impact	1,676,656	0.022
Emissions, NO_X & PM_{10}	633,827	0.008
Emissions, CO_2	4,098,316	0.054
Policy implementation	-74,683	-0.001
Overall result, NPV, EUR2020/year	17,436,804	0.228

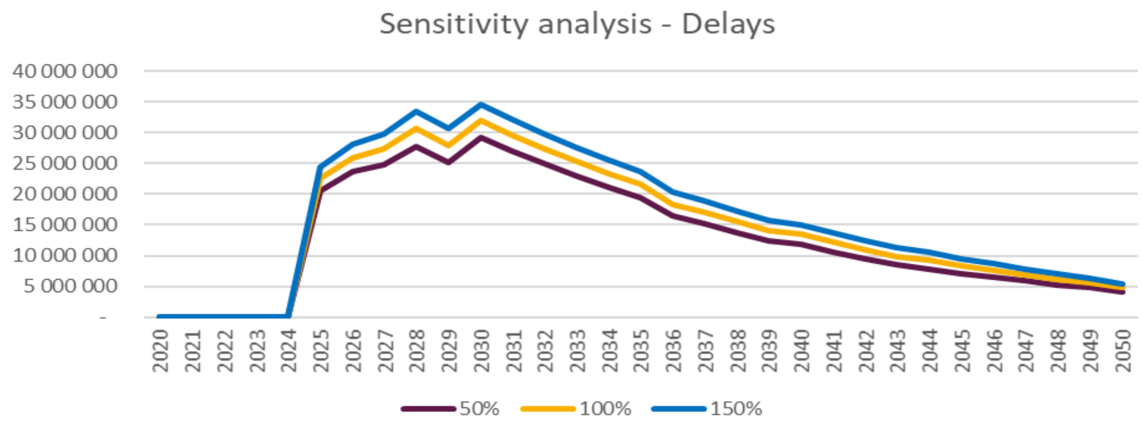
Sensitivity analysis

The CBA module conducts sensitivity analyses for the implementation cost, as well as the growth rate of amount of travel, delays, parking space and CO_2 emissions.

In this example, we show an example of the results for ±50% of the annual growth rate of average delays to traffic (seconds per vkm) as a result of high traffic volume. The impact from such a variation on the NPV is limited:

	Total NPV
50%	406,256,310
100%	453,356,908
150%	500,435,233

The figure below shows how the sensitivity analysis interval develops over time:



4.3 Summary of CBA output – hypothetical case areas

The CBA results per agent and per impact are listed for all 54 SSUCs, NPV/year and NPV/vkm, in an appendix. The following summary can be proposed, for NPV/vkm:

Regarding the travel time and internal delay impact, the hypothetical CBA shows positive NPV/vkm for AUSS and freight transport scenarios; while there are negative NPV/vkm for most passenger car scenarios, except parking space regulation and parking behaviour. The average voc will be higher under road-use pricing (city tolls) and partly also the parking scenarios. Parking space demand is reduced in automated ride sharing, GLOSA, parking behaviour, and point-to-point automated shuttle scenarios, as well as automated delivery and consolidation scenarios. The crash risk impact is negative in various passenger car scenarios, but these changes are relatively minor. There is an external delay NPV loss under parking behaviour; to a lesser extent also under automated ride sharing scenarios. Regarding emissions, most scenarios show NPV gains; the gains are relatively large under road-pricing and automated delivery and consolidation scenarios. Particularly due to the uncertainty in costs of policy implementation, one should restrain from assessments of the overall NPV.

The distributional CBA results for the "agents" show the following: Passenger car users gain from AUSS scenarios and, to a lesser extent, from freight transport scenarios; they also gain from the parking behaviour scenarios (which are not policy scenarios as such, but behavioural scenarios), while the NPV is close to zero or negative for most passenger car scenarios (in particular for high city toll levels). Public transport users gain from most deployment scenarios, except parking replacement into road traffic lanes. Freight transport providers can be expected to gain heavily from the implementation of freight transport scenarios. Changes in external effects will be beneficial under most scenarios, except parking behaviour and some ride-sharing scenarios. For the policy entity, the result in terms of NPV/vkm (all transport) will mostly follow that of the parking space, with additional gains under road-use pricing.

We stress that the CBA results for the 54 SSUCs are estimated for a hypothetical area with an incomplete set of inputs (lacking in particular a well-founded estimate of the cost of implementation). The PST user will be able to alter and correct inputs in the CBA module, such that more precise estimates can be derived for the selected policy area.

4.4 The CBA module operating within the PST

As indicated, the CBA module is developed as a spreadsheet model, building on the PST spreadsheet model version (Ziakopoulos et al. 2022). In the following, we describe how the CBA module spreadsheet is operating within the PST spreadsheet version. Supposedly, the online version of the PST will include a similar "communication" between the CBA module and the PST control unit.

In the CBA spreadsheet version, the selection of deployment scenarios (SUC and SSUC) is handled within the PST **DEMOUserInterface** (a sheet that provides most of the foundation for the initial screen in the internet version of the PST, i.e., the screen after selecting between forecasting and backcasting). The inclusion of a second SUC, for the CBA module development, is added to the DEMOUserInterface.

Based on the PST spreadsheet version enabling one SUC only, one Master DEMOUserInterface overruns all the single-SUC DEMOUSERInterface sheets (that are renamed by their official SUC name). Changing initial project year, CCAM deployment scenario, etc., in the Master DEMOUserInterface will change these to the same level in all single-SUC DEMOUSERInterface sheets. The Master DEMOUserInterface reads in the baseline matrix (impacts and years) from the selected SUC and all the SSUC alternatives numbered as "Case 1", "Case 2", etc. up to a maximum of "Case 12" (which is only relevant for the automated ride sharing SUC).

The combined SUC (two SUCs) possibility is not fully developed in the spreadsheet model; the combined policy case is described as a "Case X" in only one matrix (one table).[118] In any case, the CBA module runs on *one* selected deployment scenario; whether this is a single SSUC or a combination of two SSUCs, that doesn't really matter. The only real challenge in the communication between PST and the add-on CBA module is about the correct selection of deployment scenario from the PST into the CBA module.

Somewhat similarly, it doesn't really matter whether the specified PST baseline and policy scenario are resulting from forecasting or backcasting; the CBA module reads in *one* selected deployment scenario (one SSUC or a combination of two SSUCs) and calculates the valuations for baseline and chosen policy and estimates the changes in monetary terms (consumer surpluses, producer surpluses, etc.).

The other main input source to the CBA module is placed within the sheet **CBA_Inputs**. These inputs are the inputs, mostly valuations, that are explained in the present deliverable.

Some of the default figures presented in this deliverable ought to be possible to change for the PST user, adapting valuations etc. to his/her case area. The sheet **CBA_User_input** lists the questions to the PST user and the variables that he/she can consider; most of these with defaults.

[118] In principle, the combined cases could be listed as Case X11, …, Case X112, then Case X21, …, Case X212, etc. up to the maximum possible number (*n*) of the combined SUCs, Case X*n*1, … , Case X*n*12.

The calculations of the CBA are carried out within the sheet **CBA_Calculations**, which brings in the selected SSUC (a single or a combined), its baseline table ("baseline case") and its policy table ("chosen case"). We have shown examples in the sub-section above.

The **CBA_Calculations** sheet is building on the established Levitate structure following classes of impacts (Elvik et al. 2019): physical impacts, systemic impacts, and wider impacts. The main "sections" are as follows:

- MPR: The relevant SSUC(s), from the PST, is (are) listed at the top; then the CCAM scenario, from the PST, yielding the MPR over the project years for passenger cars and freight vehicles.
- Physical impacts: The PST variables *travel time* and *average delays* from the PST are combined with VTTS, from CBA_inputs, providing valuations of travel time and internal delay for the transport consumers. Furthermore, the *vehicle operating cost* (voc) from PST is applied in combination with transport mode multiplicators in CBA_inputs. The CBA_Inputs have specific voc input for freight vehicle; and the *freight transport cost* in the PST is applied as a voc growth factor for freight, in freight transport scenarios.
- Systemic impacts: The section applies the *amount of travel* (pkm) from the PST, for passenger transport scenarios; together with *modal split* variables and vehicle occupancies (from PST for car, from CBA_Inputs for other modes), the vkm estimates per transport mode are derived. For freight transport scenarios, the vkm set for SUCs (Hu et al. 2021a, 2021b) are applied for estimating "non-SUC freight" vkm and passenger transport vkm. The section contains a lot of details and complex formulas to ensure that the correct "agent" (transport mode) is allocated to the correct vkm for all types of SSUC and SSUC combinations.
- Wider impacts: The section applies the PST variables *road safety total effect*, *NO_X due to vehicles*, *PM_{10} due to vehicles*, and *CO_2 due to vehicles*; and firstly establish total cost using valuations from CBA_Inputs and the vkm estimates per mode (from the systemic impact section). The costs are then allocated across transport modes. In addition, *parking space* and *commuting distances* are also handled under this section. (Furthermore, there are estimations of the number of car entries into the city centre, for city toll SSUCs.)
- Monetary impacts: This section is just a small section for the exchange rate between the CBA_Inputs values in EU-28 2020 € values (for a PST/capita of 30,500) and the PST user selected PST/capita level (where 17,000 is PST default).
- Costs: This is a large section that derives infrastructure users' internal costs, external costs, and policy entity costs, per vkm, under baseline and chosen policy. It combines the calculations from the sections above with further valuations and other figures from the CBA_inputs.
- SUC-specific effects: This section resembles the section above, but some SSUCs have specific dimensions, like fees/tolls; it adds to the internal costs of some and yields an income to the policy entity (and the policy entity might face costs in acquiring land for more parking space).
- Aggregated effects: In this section, all input is combined to calculate total monetary effects for the included agents; it adds (over agents or over impacts) to total NPV for the SSUC (deployment scenario). In addition, there are break-even analysis and, if relevant, calculation of a residual value. Result tables are created.

Copies of the CBA_Calculations are implemented for the sake of producing sensitivity analyses.

The **CBA_Results** lists the main results of the CBA; results that the PST user will be shown after considering and deciding on the CBA_Inputs.

CBA_User_input applies default figure input from DEMOUserInterface; CBA_Input applies input from DEMOUserInterface and CBA_User_input; CBA_Calculations applies input from DEMOUserInterface and CBA_Input; and CBA_Results applies input from DEMOUserInterface and CBA_Calculations.

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Appendix I: CBA results, hypothetical area, per agent and impact, 54 SSUCs

The common hypothetical case area has a population size of 500,000 and, for passenger transport scenarios, an annual amount of person travel of 2 billion pkm, initially distributed 40% public transport (55% road-based), 3% active transport (50% cycle vkm), and 57% car transport. The scenarios for AUSS are scaled with respect to the amount of travel; and automated ride sharing is scaled with respect to the pkm by automated cars. For freight transport scenarios, scaling with respect to the city population is applied. Beyond that, the CBA applies defaults from the PST development version (Ziakopoulos et al., 2022).

The impacts are distributed as follows:

- Travel time & internal delay impact: a weighted average of individuals' valuation of travel time saving in "free flow" and in congestion is applied to travel time changes and delay changes.
- Vehicle operating and ownership: All transport modes' voc is derived applying multiplicators to the PST voc for passenger cars; for freight vehicles the voc is primarily based on Hu et al. (2021a; 2021b).
- Parking space (fares & fees): A hypothetical parking space value is derived from changes in the populations' required parking space and a valuation of undeveloped land. (Fares paid by public transport and shared vehicle users, as well as fees paid for parking or driving in the city centre are also channelled into this impact category, but the payments are cancelled out by the incomes for transport service providers and the policy entity.)
- Internal crash risk impact: The share of a cost of crash that a transport mode user will suffer himself/herself (injury and/or payment).
- External crash risk impact: The share of a cost of crash that is charged on collision adversaries and the rest of society (injury and/or payment).
- External delay impact: The share of the cost of delay that other infrastructure users and the rest of society will bear.
- Emissions, NO_X & PM_{10}: The local air pollutants with valuations.
- Emissions, CO_2: The global greenhouse gas with valuations.
- Policy implementation: The cost of implementing the policy, the deployment scenario (always zero or negative).

The tables below show first the NPV/year and then the NPV/vkm for all the the 54 deployment scenarios (SSUCs), from all three use cases, representing discounted average changes for a project period from 2025 to 2050. The Euro values in the tables represent EUR_{2020} for GDP/capita equal to 17,000, following the PST default.

Road use pricing, NPV/year

Impact variable	Static fee (5€)	Static fee (10€)	Static fee (100€)	Dynamic fee €0.71/km	Dynamic fee €1.4/km	Dynamic fee €14/km	Empty km fee €0.7/km	Empty km fee €1.4/km	Empty km fee €14/km
Travel time & internal delay impact	-45,603,188	-45,603,188	-45,603,188	-55,295,389	-55,295,389	-55,295,389	-38,045,278	-38,045,278	-38,045,278
Vehicle operating & ownership	-33,961,735	-33,961,735	-33,961,735	-31,189,305	-31,189,305	-31,189,305	6,700,286	6,700,286	6,700,286
Parking space (& fares, fees)	-781,740	-29,465,637	-545,775,794	-874,305	-28,897,247	-533,310,205	1,724,475	1,643,539	186,692
Internal crash risk impact	804,415	804,415	804,415	772,689	772,689	772,689	523,762	523,762	523,762
External crash risk impact	675,804	675,804	675,804	655,689	655,689	655,689	463,412	463,412	463,412
External delay impact	16,660,388	16,660,388	16,660,388	15,277,200	15,277,200	15,277,200	10,255,548	10,255,548	10,255,548
Emissions, NO_x & PM_{10}	4,824,972	4,824,972	4,824,972	4,685,341	4,685,341	4,685,341	3,326,341	3,326,341	3,326,341
Emissions, CO_2	30,844,621	30,844,621	30,844,621	29,988,179	29,988,179	29,988,179	21,440,794	21,440,794	21,440,794
Policy implementation	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844
NPV, EUR_{2020}/year	-26,580,305	-55,264,203	-571,574,359	-36,023,744	-64,046,686	-568,459,645	6,345,498	6,264,562	4,807,714

Agent	Static fee (5€)	Static fee (10€)	Static fee (100€)	Dynamic fee €0.71/km	Dynamic fee €1.4/km	Dynamic fee €14/km	Empty km fee €0.7/km	Empty km fee €1.4/km	Empty km fee €14/km
Active transport users	-188,567	-188,567	-188,567	-178,098	-178,098	-178,098	13,147	13,147	13,147
Passenger car users	-203,018,883	-355,314,253	-3,096,630,906	-211,818,665	-364,774,991	-3,117,988,822	-37,324,002	-38,125,896	-52,559,972
Public transport users	180,723	180,723	180,723	180,083	180,083	180,083	20,184,196	20,184,196	20,184,196
Public transport providers	14,153,619	14,153,619	14,153,619	14,368,432	14,368,432	14,368,432	-20,517,793	-20,517,793	-20,517,793
Freight providers	-12,394,216	-12,394,216	-12,394,216	-12,185,046	-12,185,046	-12,185,046	5,089,291	5,089,291	5,089,291
External effects	53,005,786	53,005,786	53,005,786	50,606,409	50,606,409	50,606,409	35,486,095	35,486,095	35,486,095
Policy entity	121,681,231	245,292,703	2,470,299,188	123,003,139	247,936,522	2,496,737,383	3,414,563	4,135,520	17,112,749
NPV, EUR_{2020}/year	-26,580,305	-55,264,203	-571,574,359	-36,023,744	-64,046,686	-568,459,645	6,345,498	6,264,562	4,807,714

Road use pricing, NPV/vkm

Impact variable	Static fee (5€)	Static fee (10€)	Static fee (100€)	Dynamic fee €0.71/km	Dynamic fee €1.4/km	Dynamic fee €14/km	Empty km fee €0.7/km	Empty km fee €1.4/km	Empty km fee €14/km
Travel time & internal delay impact	-0.0754	-0.0754	-0.0754	-0.0907	-0.0907	-0.0907	-0.0584	-0.0584	-0.0584
Vehicle operating & ownership	-0.0562	-0.0562	-0.0562	-0.0511	-0.0511	-0.0511	0.0103	0.0103	0.0103
Parking space (& fares, fees)	-0.0017	-0.0632	-1.1697	-0.0019	-0.0613	-1.1320	0.0032	0.0031	0.0003
Internal crash risk impact	0.0014	0.0014	0.0014	0.0013	0.0013	0.0013	0.0008	0.0008	0.0008
External crash risk impact	0.0012	0.0012	0.0012	0.0011	0.0011	0.0011	0.0007	0.0007	0.0007
External delay impact	0.0307	0.0307	0.0307	0.0279	0.0279	0.0279	0.0168	0.0168	0.0168
Emissions, NO_x & PM_{10}	0.0089	0.0089	0.0089	0.0086	0.0086	0.0086	0.0054	0.0054	0.0054
Emissions, CO_2	0.0859	0.0859	0.0859	0.0828	0.0828	0.0828	0.0536	0.0536	0.0536
Policy implementation	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
NPV, EUR_{2020}/year	-0.04	-0.09	-0.95	-0.06	-0.10	-0.93	0.01	0.01	0.01

Agent	Static fee (5€)	Static fee (10€)	Static fee (100€)	Dynamic fee €0.71/km	Dynamic fee €1.4/km	Dynamic fee €14/km	Empty km fee €0.7/km	Empty km fee €1.4/km	Empty km fee €14/km
Active transport users	-0.0031	-0.0031	-0.0031	-0.0029	-0.0029	-0.0029	0.0003	0.0003	0.0003
Passenger car users	-0.9089	-1.6030	-14.0964	-0.9380	-1.6279	-14.0472	-0.1372	-0.1420	-0.2283
Public transport users	0.0068	0.0068	0.0068	0.0068	0.0068	0.0068	1.0298	1.0298	1.0298
Public transport providers	0.5300	0.5300	0.5300	0.5416	0.5416	0.5416	-1.0468	-1.0468	-1.0468
Freight providers	-0.1621	-0.1621	-0.1621	-0.1594	-0.1594	-0.1594	0.0666	0.0666	0.0666
External effects	0.0976	0.0976	0.0976	0.0924	0.0924	0.0924	0.0581	0.0581	0.0581
Policy entity	0.2013	0.4057	4.0861	0.2016	0.4065	4.0931	0.0052	0.0063	0.0263
NPV, EUR_{2020}/year	-0.04	-0.09	-0.95	-0.06	-0.10	-0.93	0.01	0.01	0.01

Dedicated lanes / GLOSA, NPV/year

Impact variable	Motorway and A road	Motorway only	A road, right-most	A road, left-most	On 1 inter-section	On 2 inter-sections	On 3 inter-sections
Travel time & internal delay impact	-15,829,234	-26,038,269	-17,799,164	-18,361,852	-8,078,817	-7,908,689	-7,785,319
Vehicle operating & ownership	15,871,446	19,630,518	13,247,535	19,630,518	27,698,249	27,698,249	27,698,249
Parking space (& fares, fees)	-2,371,462	-2,876,609	-4,189,016	-2,876,609	-6,077,325	-6,077,325	-6,077,325
Internal crash risk impact	92,020	92,925	396,137	598,329	-28,319	183,775	167,970
External crash risk impact	84,149	78,534	360,143	533,368	-68,074	121,622	103,362
External delay impact	2,054,944	2,357,083	8,435,439	7,028,500	7,952,920	8,080,584	8,201,428
Emissions, NO_X & PM_{10}	539,451	750,398	689,215	1,102,634	412,311	421,880	417,138
Emissions, CO_2	3,438,735	5,133,985	5,542,311	7,679,022	3,429,970	3,501,238	3,467,919
Policy implementation	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844
NPV, EUR_{2020}/year	3,836,205	-915,278	6,638,755	15,290,068	25,197,071	25,977,491	26,149,578

Agent	Motorway and A road	Motorway only	A road, right-most	A road, left-most	On 1 inter-section	On 2 inter-sections	On 3 inter-sections
Active transport users	46,799	49,647	48,080	90,752	118,540	137,899	137,707
Passenger car users	-8,089,784	-17,301,484	-12,786,653	-10,169,698	242,617	580,253	667,870
Public transport users	0	0	0	0	0	0	0
Public transport providers	2,154,021	2,015,699	394,079	2,015,699	-255,018	-255,018	-255,018
Freight providers	5,320,866	7,483,519	5,859,150	8,492,449	13,413,469	13,438,697	13,458,837
External effects	6,117,279	8,320,001	15,027,107	16,343,525	11,727,127	12,125,325	12,189,846
Policy entity	-1,712,976	-1,482,659	-1,903,008	-1,482,659	-49,665	-49,665	-49,665
NPV, EUR_{2020}/year	3,836,205	-915,278	6,638,755	15,290,068	25,197,071	25,977,491	26,149,578

Dedicated lanes / GLOSA, NPV/vkm

Impact variable	Motorway and A road	Motorway only	A road, right-most	A road, left-most	On 1 inter-section	On 2 inter-sections	On 3 inter-sections
Travel time & internal delay impact	-0.0197	-0.0337	-0.0232	-0.0238	-0.0097	-0.0095	-0.0093
Vehicle operating & ownership	0.0198	0.0254	0.0173	0.0254	0.0333	0.0333	0.0333
Parking space (& fares, fees)	-0.0035	-0.0044	-0.0065	-0.0044	-0.0087	-0.0087	-0.0087
Internal crash risk impact	0.0001	0.0001	0.0005	0.0008	-0.0000	0.0002	0.0002
External crash risk impact	0.0001	0.0001	0.0005	0.0007	-0.0001	0.0001	0.0001
External delay impact	0.0027	0.0032	0.0116	0.0096	0.0101	0.0102	0.0104
Emissions, NO_X & PM_{10}	0.0007	0.0010	0.0009	0.0015	0.0005	0.0005	0.0005
Emissions, CO_2	0.0070	0.0107	0.0118	0.0161	0.0067	0.0069	0.0068
Policy implementation	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
NPV, EUR_{2020}/year	0.00	-0.00	0.01	0.02	0.03	0.03	0.03

Agent	Motorway and A road	Motorway only	A road, right-most	A road, left-most	On 1 inter-section	On 2 inter-sections	On 3 inter-sections
Active transport users	0.0011	0.0012	0.0012	0.0022	0.0027	0.0032	0.0032
Passenger car users	-0.0238	-0.0563	-0.0410	-0.0408	0.0003	0.0011	0.0012
Public transport users	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Public transport providers	0.1121	0.1058	0.0209	0.1058	-0.0123	-0.0123	-0.0123
Freight providers	0.0660	0.0928	0.0726	0.1053	0.1525	0.1528	0.1531
External effects	0.0080	0.0114	0.0207	0.0223	0.0149	0.0154	0.0154
Policy entity	-0.0021	-0.0019	-0.0025	-0.0019	-0.0001	-0.0001	-0.0001
NPV, EUR_{2020}/year	0.00	-0.00	0.01	0.02	0.03	0.03	0.03

Parking space regulation / Parking behaviour, NPV/year

Impact variable	Drive around	Balanced	Return to origin	Removing 50% parking space	Replacing with driving lanes	Replacing with cycling lanes	Replacing with pick-up drop-off	Replacing with public space
Travel time & internal delay impact	20,425,191,	6,499,441,	-1,350,705,	2,406,724,	24,821,430,	-10,814,171,	6,104,964,	-11,338,752,
Vehicle operating & ownership	-18,354,995,	-12,599,453,	-7,642,317,	6,324,526,	-21,098,280,	8,934,270,	6,324,526,	8,934,270,
Parking space (& fares, fees)	12,913,321,	45,377,802,	64,661,383,	7,470,245,	-28,813,212,	-31,671,128,	-27,866,468,	-31,689,176,
Internal crash risk impact	-882,607,	-177,272,	98,852,	141,525,	-12,116,	484,723,	98,198,	462,443,
External crash risk impact	-927,418,	-170,183,	111,313,	95,419,	-46,376,	439,611,	54,739,	417,997,
External delay impact	-18,895,934,	-12,738,026,	-13,176,393,	9,654,225,	11,815,432,	21,750,321,	12,438,395,	21,455,542,
Emissions, NO_x & PM_{10}	-3,060,731,	-3,619,357,	-3,033,468,	412,010,	1,971,389,	2,932,776,	942,412,	2,866,824,
Emissions, CO_2	-17,672,307,	-20,926,882,	-17,285,919,	2,737,443,	9,098,724,	16,741,880,	5,708,407,	16,414,761,
Policy implementation	-43,844,	-43,844,	-43,844,	-43,844,	-43,844,	-43,844,	-43,844,	-43,844,
NPV, EUR_{2020}/year	-26,499,323,	1,602,227,	22,338,903,	29,198,273,	-2,306,853,	8,754,439,	3,761,329,	7,480,067,

Agent	Drive around	Balanced	Return to origin	Removing 50% parking space	Replacing with driving lanes	Replacing with cycling lanes	Replacing with pick-up drop-off	Replacing with public space
Active transport users	-90,758	-40,147	-11,014	60,992	-33,289	84,802	57,625	83,417
Passenger car users	45,916,824	40,253,443	39,449,940	32,315	11,163,603	-10,992,257	3,148,876	-11,466,347
Public transport users	4,609,427	5,980,696	6,912,098	3,187,307	-10,906,197	-10,539,137	1,724,551	-10,511,022
Public transport providers	-4,419,545	-3,214,774	-2,324,546	-11,533,636	413,485	2,167,574	-10,092,692	2,121,410
Freight providers	-11,373,535	-8,935,201	-7,246,991	3,711,351	-8,612,385	3,340,108	4,253,071	3,268,722
External effects	-40,556,389	-37,454,448	-33,384,467	12,899,097	22,839,169	41,864,588	19,143,953	41,155,125
Policy entity	-20,585,347	5,012,657	18,943,884	20,840,846	-17,171,238	-17,171,238	-14,474,055	-17,171,238
NPV, EUR_{2020}/year	-26,499,323	1,602,227	22,338,903	29,198,273	-2,306,853	8,754,439	3,761,329	7,480,067

Parking space regulation / Parking behaviour, NPV/vkm

Impact variable	Drive around	Balanced	Return to origin	Removing 50% parking space	Replacing with driving lanes	Replacing with cycling lanes	Replacing with pick-up drop-off	Replacing with public space
Travel time & internal delay impact	0.0231	0.0078	-0.0017	0.0030	0.0264	-0.0134	0.0076	-0.0140
Vehicle operating & ownership	-0.0207	-0.0150	-0.0094	0.0078	-0.0224	0.0110	0.0078	0.0110
Parking space (& fares, fees)	0.0168	0.0633	0.0931	0.0108	-0.0352	-0.0460	-0.0404	-0.0460
Internal crash risk impact	-0.0010	-0.0002	0.0001	0.0002	-0.0000	0.0006	0.0001	0.0006
External crash risk impact	-0.0011	-0.0002	0.0001	0.0001	-0.0001	0.0006	0.0001	0.0005
External delay impact	-0.0224	-0.0160	-0.0171	0.0125	0.0131	0.0283	0.0161	0.0279
Emissions, NO_x & PM_{10}	-0.0036	-0.0046	-0.0039	0.0005	0.0022	0.0038	0.0012	0.0037
Emissions, CO_2	-0.0327	-0.0406	-0.0343	0.0055	0.0158	0.0337	0.0114	0.0331
Policy implementation	-0.0000	-0.0001	-0.0001	-0.0001	-0.0000	-0.0001	-0.0001	-0.0001
NPV, EUR_{2020}/year	-0.03	0.00	0.03	0.04	-0.00	0.01	0.00	0.01

Agent	Drive around	Balanced	Return to origin	Removing 50% parking space	Replacing with driving lanes	Replacing with cycling lanes	Replacing with pick-up drop-off	Replacing with public space
Active transport users	-0.0022	-0.0009	-0.0002	0.0017	-0.0008	0.0021	0.0016	0.0021
Passenger car users	0.1628	0.1333	0.1484	-0.0048	0.0111	-0.0434	0.0007	-0.0443
Public transport users	0.2295	0.2860	0.3199	0.1741	-0.5742	-0.5748	0.0942	-0.5733
Public transport providers	-0.2200	-0.1537	-0.1076	-0.6302	0.0218	0.1182	-0.5514	0.1157
Freight providers	-0.1462	-0.1148	-0.0932	0.0456	-0.1059	0.0411	0.0523	0.0402
External effects	-0.0480	-0.0472	-0.0432	0.0167	0.0254	0.0544	0.0248	0.0535
Policy entity	-0.0232	0.0060	0.0232	0.0258	-0.0182	-0.0212	-0.0179	-0.0212
NPV, EUR_{2020}/year	-0.03	0.00	0.03	0.04	-0.00	0.01	0.00	0.01

Automated ride sharing, NPV/year

Impact variable	5%, 20% wts	5%, 50% wts	5%, 80% wts	5%, 100% wts	10%, 20% wts	10%, 50% wts	10%, 80% wts	10%, 100% wts	20%, 20% wts	20%, 50% wts	20%, 80% wts	20%, 100% wts
Travel time & internal delay impact	-57,602,744	-54,542,882	-50,854,708	-47,536,538	-60,921,271	-60,791,943	-57,386,429	-60,921,271	-49,168,794	-47,038,114	-48,074,652	-48,054,470
Vehicle operating & ownership	19,184,465	19,724,961	20,451,410	20,806,300	16,762,654	18,075,111	19,263,427	16,762,654	11,341,858	14,252,997	16,720,824	18,189,123
Parking space (& fares, fees)	42,870,929	40,704,179	36,052,682	32,767,404	89,396,098	82,370,323	75,099,726	89,396,098	213,982,732	194,767,124	171,092,561	149,935,642
Internal crash risk impact	-182,882	-223,330	-81,335	45,846	-428,922	-268,021	-242,783	-428,922	158,754	348,497	378,581	-155,104
External crash risk impact	-255,515	-279,118	-127,641	-826	-545,059	-356,531	-302,595	-545,059	-149,948	116,026	215,825	-238,182
External delay impact	-7,570,933	-5,549,135	-2,517,683	-772,741	-9,770,026	-8,730,073	-6,013,456	-9,770,026	-2,198,837	356,766	1,029,558	1,083,478
Emissions, NO_X & PM_{10}	-107,918	-140,405	-64,679	142,015	-851,205	-568,822	-352,880	-851,205	265,891	511,617	591,713	-124,986
Emissions, CO_2	1,394,958	879,497	1,250,836	2,295,897	-1,050,510	-231,166	771,855	-1,050,510	8,344,279	8,393,293	7,356,234	2,984,304
Policy implementation	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844
NPV, EUR_{2020}/year	-2,313,485	529,922	4,065,039	7,703,513	32,547,916	29,455,034	30,793,021	32,547,916	182,532,092	171,664,362	149,266,801	123,575,960

Agent	5%, 20% wts	5%, 50% wts	5%, 80% wts	5%, 100% wts	10%, 20% wts	10%, 50% wts	10%, 80% wts	10%, 100% wts	20%, 20% wts	20%, 50% wts	20%, 80% wts	20%, 100% wts
Active transport users	101,623	99,640	113,602	125,684	69,911	87,232	93,083	69,911	89,467	117,002	127,242	87,024
Passenger car users	-44,220,408	-41,599,966	-38,269,955	-35,272,374	-47,409,679	-47,139,662	-44,151,677	-47,409,679	-37,062,571	-34,996,925	-35,788,472	-36,200,496
Public transport users	26,783,695	27,282,699	24,700,601	22,710,392	55,344,603	51,369,905	46,663,163	55,344,603	123,690,655	114,105,030	101,758,752	93,631,468
Public transport providers	24,626,522	22,475,994	21,090,929	20,125,480	40,455,358	38,647,246	37,204,323	40,455,358	92,005,848	85,116,436	76,076,987	64,376,670
Freight providers	3,111,820	3,538,045	4,066,357	4,527,314	2,481,851	2,554,233	3,058,534	2,481,851	3,724,635	4,122,445	4,076,290	4,154,010
External effects	-6,539,408	-5,089,161	-1,459,167	1,664,345	-12,216,800	-9,886,592	-5,897,076	-12,216,800	6,261,386	9,377,702	9,193,330	3,704,613
Policy entity	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328	-6,177,328
NPV, EUR_{2020}/year	-2,313,485	529,922	4,065,039	7,703,513	32,547,916	29,455,034	30,793,021	32,547,916	182,532,092	171,664,362	149,266,801	123,575,960

Automated ride sharing, NPV/vkm

Impact variable	5%, 20% wts	5%, 50% wts	5%, 80% wts	5%, 100% wts	10%, 20% wts	10%, 50% wts	10%, 80% wts	10%, 100% wts	20%, 20% wts	20%, 50% wts	20%, 80% wts	20%, 100% wts
Travel time & internal delay impact	-0.0659	-0.0630	-0.0594	-0.0558	-0.0684	-0.0697	-0.0670	-0.0684	-0.0536	-0.0535	-0.0564	-0.0573
Vehicle operating & ownership	0.0220	0.0228	0.0239	0.0244	0.0188	0.0207	0.0225	0.0188	0.0124	0.0162	0.0196	0.0217
Parking space (& fares, fees)	0.0599	0.0571	0.0508	0.0462	0.1255	0.1166	0.1071	0.1255	0.3078	0.2849	0.2527	0.2218
Internal crash risk impact	-0.0002	-0.0003	-0.0001	0.0001	-0.0005	-0.0003	-0.0003	-0.0005	0.0002	0.0004	0.0005	-0.0002
External crash risk impact	-0.0003	-0.0003	-0.0002	-0.0000	-0.0007	-0.0004	-0.0004	-0.0007	-0.0002	0.0001	0.0003	-0.0003
External delay impact	-0.0094	-0.0069	-0.0032	-0.0010	-0.0122	-0.0110	-0.0076	-0.0122	-0.0028	0.0005	0.0013	0.0014
Emissions, NO_x & PM_{10}	-0.0001	-0.0002	-0.0001	0.0002	-0.0011	-0.0007	-0.0004	-0.0011	0.0003	0.0007	0.0008	-0.0002
Emissions, CO_2	0.0028	0.0017	0.0025	0.0045	-0.0021	-0.0005	0.0015	-0.0021	0.0181	0.0179	0.0154	0.0062
Policy implementation	-0.0001	-0.0001	-0.0001	-0.0001	-0.0000	-0.0001	-0.0001	-0.0000	-0.0000	-0.0000	-0.0001	-0.0001
NPV, EUR_{2020}/year	-0.00	0.00	0.00	0.01	0.04	0.03	0.04	0.04	0.20	0.20	0.18	0.15

Agent	5%, 20% wts	5%, 50% wts	5%, 80% wts	5%, 100% wts	10%, 20% wts	10%, 50% wts	10%, 80% wts	10%, 100% wts	20%, 20% wts	20%, 50% wts	20%, 80% wts	20%, 100% wts
Active transport users	0.0023	0.0023	0.0026	0.0029	0.0016	0.0020	0.0021	0.0016	0.0020	0.0027	0.0029	0.0020
Passenger car users	-0.1220	-0.1162	-0.1087	-0.1020	-0.1329	-0.1313	-0.1239	-0.1329	-0.1204	-0.1128	-0.1123	-0.1115
Public transport users	1.0304	1.2830	1.6754	1.9781	1.2835	1.5151	1.9514	1.2835	1.4453	1.7429	2.3060	3.0696
Public transport providers	0.9621	1.0512	1.3435	1.5534	0.8721	1.1496	1.5640	0.8721	1.0607	1.4425	1.9006	2.1546
Freight providers	0.0354	0.0402	0.0462	0.0515	0.0282	0.0290	0.0348	0.0282	0.0424	0.0469	0.0464	0.0472
External effects	-0.0081	-0.0064	-0.0018	0.0021	-0.0153	-0.0124	-0.0075	-0.0153	0.0080	0.0122	0.0120	0.0048
Policy entity	-0.0071	-0.0071	-0.0072	-0.0072	-0.0069	-0.0071	-0.0072	-0.0069	-0.0067	-0.0070	-0.0073	-0.0074
NPV, EUR_{2020}/year	-0.00	0.00	0.00	0.01	0.04	0.03	0.04	0.04	0.20	0.20	0.18	0.15

Point-to-point two hubs / Point-to-point larger network / On-demand, NPV/year

Impact variable	Peak hour, mixed traffic	Peak hour, dedicated lane	Peak hour, incident	Peak hour, mixed traffic	Off-peak hour, dedicated lane	Peak hour, mixed traffic	Peak hour, dedicated lane	Off-peak hour, mixed traffic	5%, 8 pax	5%, 15 pax	10%, 8 pax	10%, 15 pax
Travel time & internal delay impact	970,821	-10,779,733	33,798,736	8,530,501	34,038,631	8,601,735	8,394,119	32,903,519	22,377,939	22,264,743	24,395,329	23,657,209
Vehicle operating & ownership	9,817,098	9,817,098	9,817,098	9,817,098	9,817,098	9,839,734	9,839,734	9,839,734	4,751,988	4,773,155	7,931,087	7,970,658
Parking space (& fares, fees)	6,810,186	6,810,186	6,810,186	6,810,186	6,810,186	6,704,187	6,704,268	6,698,575	-14,097,312	-13,789,836	-17,956,308	-17,629,427
Internal crash risk impact	660,816	610,657	1,238,624	909,974	2,226,459	586,878	568,066	2,131,950	-82,242	-73,950	38,620	41,711
External crash risk impact	642,886	593,475	1,097,299	841,300	2,048,411	539,840	522,315	1,937,165	-62,795	-54,900	44,984	48,204
External delay impact	5,734,742	-2,070,230	33,390,047	13,634,575	29,244,413	11,812,129	11,605,497	27,967,349	8,626,727	8,592,868	12,020,804	11,597,602
Emissions, NO_x & PM_{10}	-981,062	-1,770,636	2,360,632	5,715,726	5,808,228	686,321	713,213	3,191,893	182,491	273,367	623,269	650,282
Emissions, CO_2	-4,955,760	-10,056,027	22,818,862	47,908,244	48,149,665	4,687,887	4,882,106	24,508,191	1,328,208	1,832,380	4,355,693	4,517,753
Policy implementation	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844	-43,844
NPV, EUR_{2020}/year	18,655,883	-6,889,054	111,287,640	94,123,761	138,099,247	43,414,867	43,185,473	109,134,533	22,981,160	23,773,983	31,409,635	30,810,149

Agent	Peak hour, mixed traffic	Peak hour, dedicated lane	Peak hour, incident	Peak hour, mixed traffic	Off-peak hour, dedicated lane	Peak hour, mixed traffic	Peak hour, dedicated lane	Off-peak hour, mixed traffic	5%, 8 pax	5%, 15 pax	10%, 8 pax	10%, 15 pax
Active transport users	62,495,	59,453,	131,203,	91,360,	196,125,	53,278,	51,863,	182,062,	-39,765,	-39,042,	-19,583,	-19,404,
Passenger car users	6,242,380,	-4,003,968,	34,754,787,	12,773,169,	36,083,642,	12,703,677,	12,510,751,	35,059,034,	19,517,835,	19,425,847,	20,800,296,	20,168,308,
Public transport users	0,	0,	0,	0,	0,	82,606,	82,687,	76,994,	300,106,	-520,671,	-1,311,457,	-1,328,483,
Public transport providers	7,070,998,	7,070,997,	7,071,053,	7,071,021,	7,071,100,	6,904,774,	6,904,772,	6,904,955,	-6,025,260,	-4,875,785,	-6,934,805,	-6,551,140,
Freight providers	5,660,126,	4,108,804,	10,484,679,	6,909,286,	10,318,585,	6,765,276,	6,733,190,	10,127,811,	5,114,570,	5,100,875,	7,791,390,	7,687,983,
External effects	440,805,	-13,303,418,	59,666,839,	68,099,846,	85,250,716,	17,726,177,	17,723,131,	57,604,598,	10,074,630,	10,643,715,	17,044,750,	16,813,840,
Policy entity	-820,921,	-820,921,	-820,921,	-820,921,	-820,921,	-820,921,	-820,921,	-820,921,	-5,960,956,	-5,960,956,	-5,960,956,	-5,960,956,
NPV, EUR_{2020}/year	18,655,883,	-6,889,054,	111,287,640,	94,123,761,	138,099,247,	43,414,867,	43,185,473,	109,134,533,	22,981,160,	23,773,983,	31,409,635,	30,810,149,

Point-to-point two hubs / Point-to-point larger network / On-demand, NPV/vkm

Impact variable	Peak hour, mixed traffic	Peak hour, dedicated lane	Peak hour, incident	Peak hour, mixed traffic	Off-peak hour, dedicated lane	Peak hour, mixed traffic	Peak hour, dedicated lane	Off-peak hour, mixed traffic	5%, 8 pax	5%, 15 pax	10%, 8 pax	10%, 15 pax
Travel time & internal delay impact	0.0012	-0.0130	0.0406	0.0103	0.0409	0.0103	0.0101	0.0395	0.0307	0.0305	0.0345	0.0334
Vehicle operating & ownership	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0118	0.0065	0.0065	0.0112	0.0113
Parking space (& fares, fees)	0.0098	0.0098	0.0098	0.0098	0.0098	0.0096	0.0096	0.0096	-0.0232	-0.0227	-0.0305	-0.0300
Internal crash risk impact	0.0008	0.0008	0.0015	0.0011	0.0028	0.0007	0.0007	0.0026	-0.0001	-0.0001	0.0001	0.0001
External crash risk impact	0.0008	0.0007	0.0014	0.0010	0.0025	0.0007	0.0006	0.0024	-0.0001	-0.0001	0.0001	0.0001
External delay impact	0.0073	-0.0026	0.0425	0.0174	0.0372	0.0150	0.0148	0.0356	0.0126	0.0126	0.0181	0.0175
Emissions, NO_x & PM_{10}	-0.0012	-0.0023	0.0030	0.0073	0.0074	0.0009	0.0009	0.0041	0.0003	0.0004	0.0009	0.0010
Emissions, CO_2	-0.0097	-0.0197	0.0448	0.0941	0.0946	0.0092	0.0096	0.0481	0.0030	0.0041	0.0100	0.0104
Policy implementation	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001	-0.0001
NPV, EUR_{2020}/year	0.02	-0.01	0.13	0.11	0.17	0.05	0.05	0.13	0.03	0.03	0.04	0.04

Agent	Peak hour, mixed traffic	Peak hour, dedicated lane	Peak hour, incident	Peak hour, mixed traffic	Off-peak hour, dedicated lane	Peak hour, mixed traffic	Peak hour, dedicated lane	Off-peak hour, mixed traffic	5%, 8 pax	5%, 15 pax	10%, 8 pax	10%, 15 pax
Active transport users	0.0014	0.0013	0.0028	0.0020	0.0043	0.0012	0.0011	0.0040	-0.0009	-0.0009	-0.0005	-0.0005
Passenger car users	0.0232	0.0047	0.0670	0.0311	0.0762	0.0338	0.0335	0.0754	0.0578	0.0575	0.0620	0.0605
Public transport users	0	0	0	0	0	0.2032	0.2034	0.1894	1.9420	3.5926	1.8087	3.5028
Public transport providers	2.3912	2.3912	2.3914	2.3913	2.3916	1.2488	1.2488	1.2493	1.8711	4.0110	1.7597	3.8563
Freight providers	0.0629	0.0457	0.1165	0.0768	0.1147	0.0752	0.0748	0.1125	0.0669	0.0667	0.1019	0.1006
External effects	0.0006	-0.0169	0.0760	0.0867	0.1086	0.0226	0.0226	0.0733	0.0147	0.0156	0.0256	0.0253
Policy entity	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0010	-0.0082	-0.0082	-0.0084	-0.0084
NPV, EUR_{2020}/year	0.02	-0.01	0.13	0.11	0.17	0.05	0.05	0.13	0.03	0.03	0.04	0.04

Delivery / Consolidation / Hub to hub, NPV/year

Impact variable	Semi-automated	Fully automated	Fully automated night	Manual consoli-dation	Aut. consoli-dation	Transfer hub
Travel time & internal delay impact	2,358,170	3,403,185	-21,554,405	1,691,420	3,492,525	1,312,924
Vehicle operating & ownership	1,834,226	6,771,296	5,250,184	-347,122	6,961,920	5,027,949
Parking space (& fares, fees)	1,605,112	1,605,112	35,043,876	79,172	79,172	-802,327
Internal crash risk impact	23,968	26,566	36,727	23,031	45,285	-132,698
External crash risk impact	502,138	503,593	514,383	496,863	523,787	329,054
External delay impact	761,883	1,417,576	-12,114,802	781,633	1,694,989	621,395
Emissions, NO_x & PM_{10}	632,295	630,360	630,360	27,181	633,827	9,256
Emissions, CO_2	4,098,316	4,098,316	4,098,316	225,002	4,098,316	461,730
Policy implementation	0	0	0	-74,683	-74,683	-18,671
NPV, EUR_{2020}/year	11,816,107	18,456,004	11,904,639	2,902,497	17,455,137	6,808,612

Agent	Semi-automated	Fully automated	Fully automated night	Manual consoli-dation	Aut. consoli-dation	Transfer hub
Active transport users	8,433	8,731	9,293	8,583	9,523	-2,313
Passenger car users	494,715	1,222,596	-16,330,160	207,165	1,005,819	197,737
Public transport users	0	0	0	0	0	0
Public transport providers	0	0	0	0	0	0
Freight providers	3,713,216	8,969,721	53,373	1,151,581	9,484,391	6,012,751
External effects	5,994,631	6,649,845	-6,871,743	1,530,678	6,932,586	1,421,435
Policy entity	1,605,112	1,605,112	35,043,876	4,490	4,490	-820,997
NPV, EUR_{2020}/year	11,816,107	18,456,004	11,904,639	2,902,497	17,436,804	6,808,612

Delivery / Consolidation / Hub to hub, NPV/vkm

Impact variable	Semi-automated	Fully automated	Fully automated night	Manual consoli-dation	Aut. consoli-dation	Transfer hub
Travel time & internal delay impact	0.0302	0.0424	-0.2686	0.0222	0.0456	0.0163
Vehicle operating & ownership	0.0235	0.0844	0.0654	-0.0046	0.0909	0.0625
Parking space (& fares, fees)	0.0366	0.0366	0.7984	0.0018	0.0018	-0.0183
Internal crash risk impact	0.0003	0.0003	0.0005	0.0003	0.0006	-0.0017
External crash risk impact	0.0065	0.0064	0.0065	0.0066	0.0070	0.0042
External delay impact	0.0101	0.0183	-0.1564	0.0107	0.0227	0.0080
Emissions, NO_X & PM_{10}	0.0084	0.0081	0.0081	0.0004	0.0086	0.0001
Emissions, CO_2	0.0949	0.0905	0.0905	0.0055	0.0986	0.0102
Policy implementation	0	0	0	-0.0010	-0.0010	-0.0002
NPV, EUR_{2020}/year	0.15	0.23	0.15	0.04	0.23	0.08

Agent	Semi-automated	Fully automated	Fully automated night	Manual consoli-dation	Aut. consoli-dation	Transfer hub
Active transport users	0.0030	0.0031	0.0033	0.0031	0.0034	-0.0008
Passenger car users	0.0162	0.0379	-0.7961	0.0018	0.0265	0.0027
Public transport users	0	0	0	0	0	0
Public transport providers	0	0	0	0	0	0
Freight providers	0.8514	1.3648	0.5406	0.2622	3.3920	0.7476
External effects	0.0795	0.0859	-0.0887	0.0209	0.0940	0.0183
Policy entity	0.0205	0.0200	0.4367	0.0001	0.0001	-0.0102
NPV, EUR_{2020}/year	0.15	0.23	0.15	0.04	0.23	0.08

The LEVITATE SUCs vary considerably in terms of impacts and agents affected, positively or negatively. For some SUCs there is also relatively large variation across SSUCs.

Appendix II: List of formula notations

Notation for principal aggregated benefit measures:

ΔCS – change in consumer surplus due to implemented policy

ΔPS – change in producer (service provider) surplus due to implemented policy

$\Delta M_{\mathrm{external}}$ – change in society's monetised external effects (congestion, road safety, air pollution, green house gas)

ΔPE – change in policy entity's payment collection

$C_{\mathrm{impl\_usecase\_suc\_ssuc}}$ – policy implementation (PI) cost, use case, SUC, sub-SUC

Examples of notation for implementation cost formuals (for policy entity):

$C_{\mathrm{impl\_auss\_two\_peakmix}}$ – policy implementation (PI) cost, shuttle bus - AUSS, point-to-point connecting two modes, peak hour – mixed traffic

$C_{\mathrm{impl\_car\_rup\_dyn}}$ – PI cost, passenger car, road use pricing, dynamic toll

$C_{\mathrm{impl\_freight\_autdel\_night}}$ – PI cost, freight, automated delivery, night shifts only

Examples of notation for infrastructure users' shares, valuations, and rates, that remain the same with and without PI:

$s_{\mathrm{traveltime\_cycle}}$ – share of cycling of all active transport travel time

$s_{\mathrm{traveltime\_walk}}$ – share of walking of all active transport travel time

$s_{\mathrm{km\_cycle}}$ – share of cycling of all active transport km

$s_{\mathrm{km\_walk}}$ – share of walking of all active transport km

$s_{\mathrm{pkm\_public\_road}}$ – share of road-based public transport, of all public transport pkm

$s_{\mathrm{pkm\_public\_rail}}$ – share of rail-based public transport, of all public transport pkm

$s_{\mathrm{pkm\_mancar}}$ – share of manual cars, of all passenger car passenger km (pkm)

$s_{\mathrm{vkm\_mancar}}$ – share of manual cars, of all passenger car vehicle km (vkm)

$s_{\mathrm{vkm\_aut1car}}$ – share of automated 1st generation automated ("cautious") cars, of all passenger car vkm

$s_{\mathrm{vkm\_aut2car}}$ – share of automated 2nd generation automated ("aggressive") cars, of all passenger car vkm

$s_{\mathrm{vkm\_manfreight}}$ – share of manual freight vehicles, of all freight vehicle vkm

$s_{\mathrm{vkm\_autfreight}}$ – share of automated freight vehicles, of all freight vehicle vkm

$s_{\mathrm{vkm\_LCV}}$ – share of light commercial vehicles (LCV), of all freight vehicle vkm

$s_{\mathrm{vkm\_HGV}}$ – share of heavy goods vehicles (HGV), of all freight vehicle vkm

$s_{\mathrm{tkm\_LCV}}$ – share of light commercial vehicles (LCV), of all freight vehicle tonne km (tkm)

$s_{\mathrm{tkm\_HGV}}$ – share of heavy goods vehicles (HGV), of all freight vehicle tkm

$k_{\mathrm{pkm\_cong\_car}}$ – share of pkm by passenger cars carried out under congestion, of all passenger car pkm

$k_{\mathrm{tkm\_cong\_freight}}$ – share of tkm by freight vehicles carried out under congestion, of all freight vehicle tkm

$w_{\mathrm{hour\_active}}$ – value of travel time savings (VTTS) per hour, active transport

$w_{\mathrm{hour\_flow\_mancar}}$ – value of travel time savings (VTTS) per hour under free-flow, manual car

$w_{\mathrm{hour\_cong\_autshuttle}}$ – value of travel time savings (VTTS) per hour under congestion, automated shuttle

$\bar{\theta}_{\mathrm{vkm\_mancar}}$ – relative crash cost rate, vkm, manual cars

$\bar{\theta}_{\mathrm{vkm\_autcar}}$ – relative crash cost rate, vkm, automated cars

$\bar{\theta}_{\mathrm{vkm\_active}}$ – relative crash cost rate, vkm, active transport users

$\bar{\theta}_{\mathrm{vkm\_manfreight}}$ – relative crash cost rate, vkm, manual freight vehicles

$\bar{\theta}_{\mathrm{vkm\_autfreight}}$ – relative crash cost rate, vkm, automated freight vehicles

Examples of notation for infrastructure users' variables, that might differ with and without PI:

GC^1 – generalised costs of travel, with PI

GC^0 – generalised costs of travel, without PI

GC^0_{mancar} – generalised costs of travel for users of manual cars, without PI

GC^0_{active} – generalised costs of travel for cyclists and pedestrians, without PI

$h^0_{\mathrm{min\_5km\_car}}$ – average travel time in min per 5km (in city centre) by passenger car, without PI

$h^0_{\mathrm{min\_km\_freight}}$ – average travel time in min per km (in city centre) by freight vehicle, without PI

$d^0_{\mathrm{sec\_km\_car}}$ – average delay in sec per vkm for passenger car, without PI

$d^0_{\mathrm{sec\_km\_autcar}}$ – average delay in sec per vkm for automated cars, without PI

$d^0_{\mathrm{sec\_km\_manfreight}}$ – average delay in sec per vkm for manual freight vehicles, without PI

$k^0_{\mathrm{traveltime\_cong\_mancar}}$ – share of travel time by manual cars carried out under congestion, of all manual car travel time, without PI

$k^0_{\mathrm{traveltime\_cong\_autfreight}}$ – share of travel time by automated freight vehicles carried out under congestion, of all automated freight vehilce travel time, without PI

T^0 – sum of vkm, all transport modes, without PI

$T^0_{\mathrm{safety\_passenger}}$ – sum of vkm of transport modes included in road safety calculations under passenger transport scenarios (passenger cars and active transport), without PI

$T^0_{\mathrm{safety\_freight}}$ – sum of vkm of transport modes included in road safety calculations under freight transport scenarios (freight vehicles and passenger cars), without PI

T_{car}^{0} – vkm by passenger cars, without PI

T_{aut2car}^{0} – vkm by automated 2nd generation automated cars, without PI

$n_{\mathrm{occ\_autshuttle}}^{0}$ – average occupancy in automated shuttles, without PI

$n_{\mathrm{occ\_public}}^{0}$ – average occupancy in (other) public transport, without PI

Q^{0} – sum of pkm, all modes, without PI

Q_{active}^{0} – passenger kilometres (pkm) by active transport, without PI

$\bar{C}_{\mathrm{crash}}$ – average cost per crash

N_{crash}^{0} – total number of crashes, without PI

$C_{\mathrm{crash\_mancar}}^{0}$ – total crash cost attributed to manual passenger cars, without PI

$c_{\mathrm{crash\_vkm\_autfreight}}^{0}$ – crash cost per vkm for automated freight vehicles